Bit Bang 7:

Future of Energy

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Aalto University's
Multidisciplinary Institute of
Digitalisation and Energy (MIDE)

ISBN 978-952-60-1097-7 (pbk)
ISBN 978-952-60-1098-4 (pdf)

Cover: Nanna Särkkä
Layout: Unigrafia Oy
Printed by: Unigrafia Oy, 2015

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Foreword

This book is the 7th in the Bit Bang series of books produced as multidisciplinary teamwork exercises by doctoral students participating in the course Bit Bang 7: Future of Energy at Aalto University. The course was facilitated by Professor Yrjö Neuvo, Research Director and former Nokia Chief Technology Officer; and Professor Erkki Ormala, former Vice President of Nokia. 23 students took part in the course during the academic year 2014-2015. The students were selected from diverse academic and cultural backgrounds: 12 nationalities were represented by students from the Aalto schools of Electrical Engineering, Arts, Science, Engineering, Chemistry and Business, leading to spirited in-class discussions and multidisciplinary teamwork.

The learning objectives of the course centered on teamwork, multidisciplinary collaboration, and gaining global perspectives and foresight on the future of the energy sector. These were achieved through weekly lectures from visiting industry leaders, writing the chapters of this book, and other teamwork assignments.

As textbook material and to support class discussions and teamwork the students used *The Innovator's Solution* by Clayton M. Christensen and Michael E. Raynor, *Sustainable Energy — without the hot air* by David JC MacKay, as well as selected chapters from earlier Bit Bang publications.

Working in teams, the students set out to answer questions related to the future of the energy sector. The growing global demand for energy, and diminishing natural resources are driving the development of eco-efficient energy sources, new ways of doing business, and designing our living environment. Bit Bang 7 addressed the topic of energy sources and technologies from the perspective of their economic, environmental and social sustainability. The course elaborated on the interconnectedness of these phenomena, and linked them to possible future scenarios, global megatrends and ethical considerations.

By the end of the autumn term, four teams had produced four points of view on the future of energy published in this book: *Powering Future Eco-Cities*, *How Can We Change the Everyday Energy Consumption Patterns of Citizens*, *Future of Energy: Powered by Solar* and *Toward Prosperity: Sustainable Energy Solutions for Rural Africa.*

At the start of the spring term, the groups were reshuffled and set to tackle new topics: *Energy Abundance - Curse or Blessing, Can Greenland be Green?, Fossil Fuel Divestment: of Money and Morality*, and *Energy in Science Fiction Literature*.

During the spring term, the course also visited Shanghai for a week-long study tour. The tour program and short reports on the company and institution visits are available in the appendices of this book.

The Bit Bang series of courses is funded by the Multidisciplinary Institute of Digitalisation and Energy (MIDE). The unique nature of the course has generated lots of positive feedback from the academic community, and produced an extensive network of alumni connecting doctoral student and graduated doctors. We are very proud of the community we have been able to gather around this unique and though-provoking course.

We wish to give our special thanks to this year's tutors and Bit Bang alumni Aleksandre Asatiani, Albert Hernandez Estrada. Vilen Looga and Sanja Šćepanović for their tireless work with their teams and valuable advice given whenever needed. We also wish to thank our esteemed guest lecturers representing government, industry and academia. Their presentations and discussions gave valuable insight into the issues studied, and their role was essential for the success of the course.

We wish you captivating moments with the book!
Yrjö Neuvo, Erkki Ormala and Meri Kuikka

Future of Energy

Powering Future Eco-Cities

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Abstract. The fast rate of urbanisation has resulted in many problems and risks, especially in contexts of currently developing cities or countries. The urban population of today is still mostly dependent on fossil fuels for energy, and with the current extent of urbanisation, the development will not be sustainable with the inherently limited supply of fossil fuels.

The drive for so-called eco-cities is not a particularly new concept; however, numerous complex challenges still exist as barriers to achieving sustainable development objectives. In this study, we investigate critical aspects of sustainable urban growth, with focus on the integration of renewable energy sources, by examining examples of the marriage between renewable energy and urban development in cities around the world. We uncover the underlying factors and discuss the opportunities that renewable energy provides for smart urban planning. In doing so, we propose a possible solution to the future of eco-cities, and thus a way of better urban management with renewable energy, to prevent the symptoms of a fossil fuel–based urbanisation. Renewable energy needs to go hand in hand with urban development on our path into the future.

Keywords: urbanisation, renewable energy, urban planning, sustainable policy, eco-city

1 Introduction: Urbanisation and Energy

In 1800, only 3% of the world's population lived in urban areas [1]. The phenomena of dependence on oil and urbanisation have occurred together. Historically, intensive use of fossil fuels in urban centres has resulted in dysfunctional urban structures, in terms of centralized transportation networks, construction machinery, industrial systems, manufacturing processes, intensive economic activity, and labour markets [2], which have led to many secondary and tertiary problems within the development of cities. The ugly truth is that fossil fuels are inherently limited in quantity, and the need to increasingly adopt alternative and renewable sources of energy is well recognized globally.

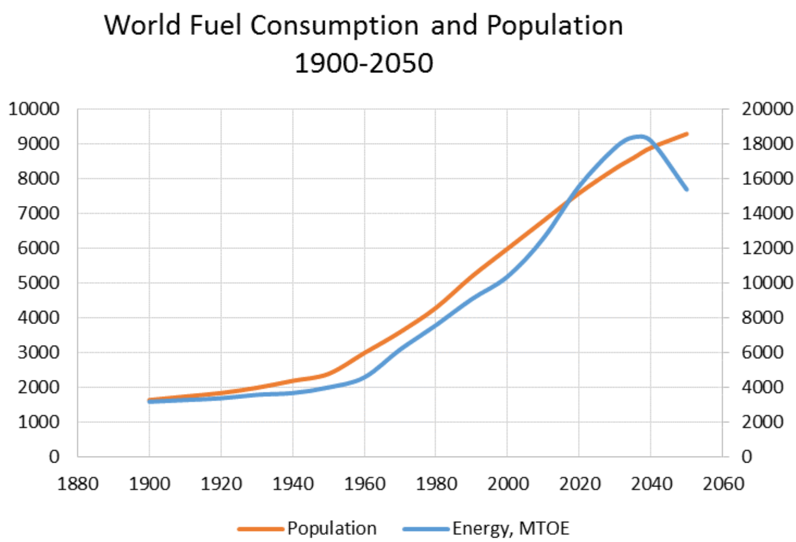

Fig. 1. ***World fuel consumption and population in 1900–2050 [3]***

The global primary energy demand is expected to rise by approximately 30–40% by 2035 with scenarios based on current policies (see Fig. 1). Even the lowest estimates of future energy demand suggest an increase of roughly 11%. Such a small increase would be possible only by global carbon dioxide (CO_2) pricing. Most of the growth in energy demand will be coming from countries that are not members of the Organization for Economic Cooperation and Development (OECD) and mainly from urbanisation. More specifically, the urbanisation is attributed to average urban income levels being higher than those in in rural areas, which leads to increasing use of energy. At the same time, the standard of living is rising in many recently urbanized countries, leading to more energy-intensive lifestyles. On the other hand, in OECD countries, where high living standards have already been reached, the total energy demand is actually decreasing. This is also attributed to slow population growth in OECD countries, as well as improved energy-efficiency usage [4], [5].

Given the projected rise in energy demand, it is fair to assume that the share of renewable energy sources will indeed rise substantially in the future leading up to 2035, as shown in Fig. 2. Given the growth pains exhibited in many developed countries today, there is an evident necessity for improvements in the approaches toward renewables. There are many lessons to be learned and mistakes to be acknowledged from past examples, which can be synthesized into principles for a better road to adopting and integrating renewable energy into urban development to ensure sound and robust societies, rid of past problems of urbanisation. This is particularly valuable for developing cities and countries that are aiming to increase their energy production based on renewable sources while maintaining or improving the level of socioeconomic conditions.

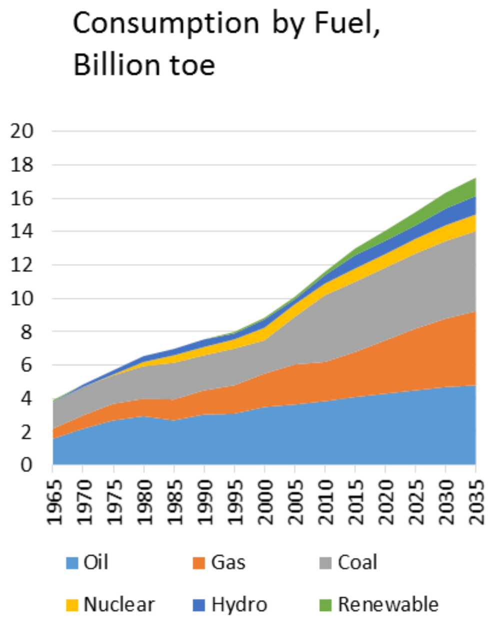

Fig. 2. ***Energy consumption by fuel [6]. (TOE: Tonne of Oil Equivalent).***

In this study, we take a critical look into the stories of successes and failures of relevant example cities from the past and present, spanning Africa, South America, and Asia. These example cities are chosen based on the diversity of their challenges and their aptness as potential stereotypes for other cities, particularly in the developing world. We synthesize the elements of past experiences regarding integrating renewable sources into urban development, with particular focus on the demands of urbanisation and the improvements enabled through sound urban planning, policy implementation, and embrace of technological innovations, and how renewable energy has played a part in driving the healthy development of cities. These principles and lessons learned are conferred and applicable as recommendations on how urban development can best be approached in sight of the inevitable requirement of integrating renewable energy into the otherwise fossil fuel–dominated mentalities. In our study, we also try to address the needs of renewable energy development and discuss whether smooth transition or integration into the current infrastructure can be achieved.

In the following sections we first discuss the present state of urbanisation and population growth, its trends and challenges. Then we present the feasibility and use of renewable sources, as well as some of the benefits they bring by default over the use of fossil fuels. After that, we analyse a few cases of how renewable energy strategies have been used in tandem with urban development plans to achieve sustainable growth and avoid or mitigate many problems associated with high rates of urbanisation. From these examples, principles and success factors are identified and applied to a future optimal scenario. The scenario includes a synthesis of critical considerations toward adopting renewables to achieve a healthy sustainable urban future and our vision of the future eco-city concept.

2 The Population Race

The current levels of urbanisation are unprecedented, as is the number and size of the world's largest cities. In 1950, there were only two megacities (cities with more than 10 million inhabitants), Tokyo and New York, and five cities with populations ranging from 5 million to 10 million inhabitants. Today, there are 21 megacities, including 17 in the developing world. Despite their visibility and dynamism, megacities account for less than 10% of the world's urban population. A majority of Africa's urban population lives in small cities (with fewer than half a million inhabitants), and so does Europe's. Urban dwellers in Asia, Latin America and the Caribbean, and North America are more concentrated in large urban agglomerations, with around 20% of their respective populations living in cities with at least 5 million inhabitants [7].

By the middle of 2009, for the first time in history, the number of people living in urban areas had surpassed the number living in rural areas, and since then the world has become more urban than rural [7]. Fig. 3 shows the rural and urban populations from 1950–2050. Urban areas are currently the home for 3.5 billion people, comprising 50.5% of the world's population. Recently, the rate of urbanisation has started to decrease, mainly because many regions have already reached a high level of urbanisation. In Europe, Latin America and the Caribbean, Oceania, and North America, 70–82% of the population lives in urban settlements. The process of urbanisation in developing countries differs significantly from the view of city life in the Western world: Every third urban dweller in Latin America and the Caribbean lives in a slum in poor conditions [7]. Also, the amount of poor people is expected to increase and make a significant contribution to the projected urban growth. Although the urbanised and developing regions of Latin America still experience net transfer from rural to city, this accounts for only one-third of urban growth [7].

The speed and scale of urbanisation in developing regions challenge the capacity of governments to adequately plan and meet the needs of the growing number of urban dwellers. As cities grow, managing them becomes more complex as their populations become more diverse. Developing countries will need to adjust to this process much faster than developed countries did in the past.

Much of urban growth is due to natural increase as the total world population continues to grow, and this natural increase tends to be realised by the poor. Three-

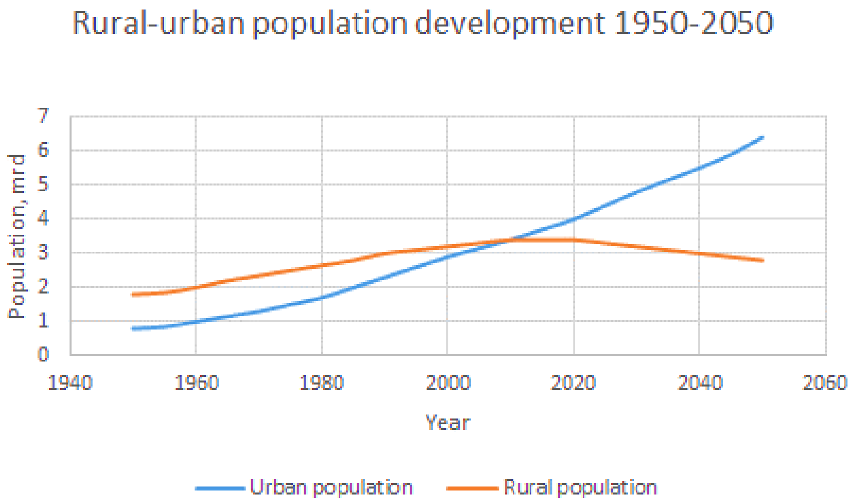

Fig. 3. Rural and urban populations globally [8]

quarters of all urban population at the moment comes from medium- and low-income groups of countries [9]. Developing countries are not equipped with the infrastructures, policies, and institutions needed to cope with this pace of development, resulting in poorly managed urban cities. This excess urbanisation, beyond the manageable pace, causes various problems related to deficiency in public infrastructure services, air pollution, and housing shortages [10].

The areas in Africa and Asia are soon to experience high intensities of urbanisation, as 83% of urban growth between 2000 and 2030 is expected to come from Africa and Asia alone. On average, Africa and Asia are around 40% urban, so many countries there are still to face the urban transition, where population shifts from being primarily rural to primarily urban [7]. The speed of this change in living environment exerts a significant stress to the energy production scheme, as people move from the proximity of traditional renewable energy source, biomass or specifically wood, to be connected to the grid for electricity. The prevalence of slums with poor heating and electricity connections in fast-developing regions is a proof that many cities are struggling to meet this increase in energy demand. In sub-Saharan Africa the fraction of urban population living in slums is a staggering 72%, and in some regions in Asia the same number reaches two-thirds. Interestingly, although Africa and Asia are still mostly rural, they have the highest urban density, that is, the smallest area for urban inhabitants to live in [7].

The hotspots of energy consumption in the dense cities pose a challenge for all kinds of energy production, not to mention renewable and sustainable energy technologies. Urbanisation itself accounts for a vast amount of energy resources. Buildings can account for 40–60% of total urban energy consumption. Cities are centres of resource consumption. Transportation of goods and services typically accounts for about 25% of energy consumption and may increase during the shift from rural to urban lifestyle [11]. Another aspect of urbanisation is the expansion of urban areas, which cannot be ignored in sight of land-use issues. The built-up urban areas currently take 0.3% of total world acreage, which may not seem like much, but the phenomenon of urban sprawl in developing countries results in serious local environmental problems [12]. By allowing the cities to grow uncontrollably, the urban expansion destroys the land in its vicinity, possibly nullifying chances for sustainable growth and access to renewable energy. Slums in particular are a big problem because the informal settlements lack sufficient waste treatment strategies and follow no guidelines for expanding.

With the seemingly overwhelming challenges imposed by the extreme rate of urbanisation in the modern age, heightened awareness in this regard is imperative—in particular, how renewable energy can be smartly coupled to address the many problems of urbanised, high-concentration societies. This is especially relevant for developing nations suffering from such terrible symptoms, and where much of the past 'mistakes' from the developed world could potentially be avoided through a change in mentality as a precursor to taking the correct actions. In the following section we discuss the energy aspects relating to renewable sources.

3 Energising the Urbanisation

In this section we discuss how various energy solutions are used in the urbanising world. The fundamental differences and the current trends concerning modern fossil fuels and renewable energy sources give rise to an idea of how future cities would look when they are designed from the energy perspective.

The use of biomass has a key role today as an energy source in developing countries. Traditional biomass accounts for more than 50% of total energy in some of these countries. According to the statistical trends, the share of biomass increases with an increase in percentage of rural population. In addition, small gross national product correlates with high usage of traditional biomass [13]. The population lacking modern energy sources counts as many as 2.4 billion. In other words, economic growth is being limited by the lack of modern energy sources for a huge proportion of the world's population. Obviously, social and environmental problems are also connected to the use of traditional biomass, creating the need for modernising the use of biomass and making it sustainable. For instance, in Nigeria the use of wood as fuel is causing deforestation, desertification, erosion, and loss of biodiversity [14]. The causes behind the use of wood as fuel were tightly linked to urbanisation and rural-to-urban migration. This is due to energy source preference, as well as lack and unaffordability of more convenient energy sources.

Because a significant proportion of energy used in developing countries is from biomass, modern technologies can create sustainable alternatives. They have the

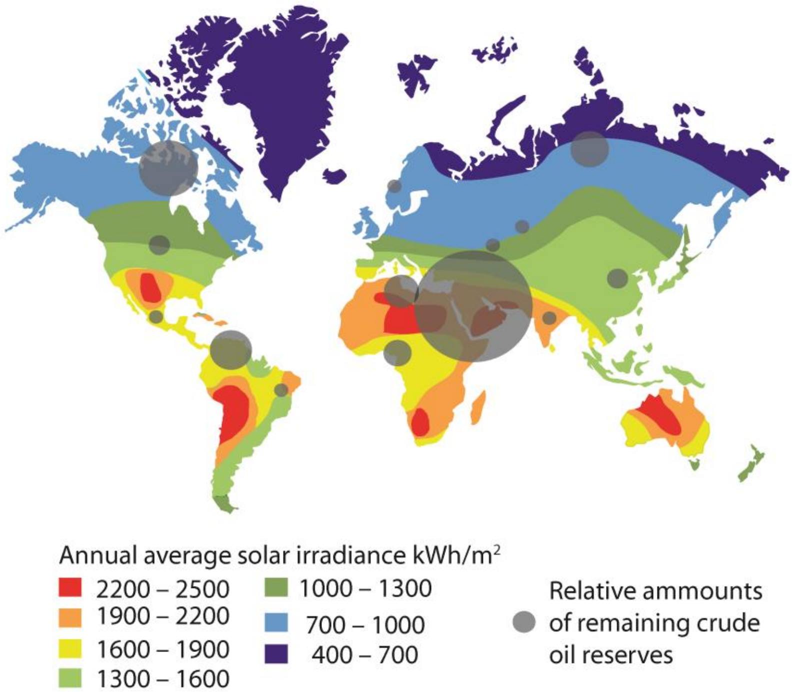

Fig. 4. ***Geographical distribution of average annual solar irradiance and known crude oil deposits***

potential to solve a wide range of problems, as well as to be converted into biofuels for transportation. Transmission and distribution of fossil fuels and energy generated from them is a concern at many places due to lack of infrastructure. However, local production of renewable energy could facilitate economic and social development as long as local conditions are taken into account. The costs of renewables can be very high considering the income of the population in remote and rural locations [15].

The renewable energy sources are typically far more conveniently distributed than fossil fuels. Oil deposits are geographically located at particular locations. Hence, roughly 95% of the known reserves are located within the borders of 10 countries that have the largest crude oil reserves [16]. The situation is similar for a few types of renewable energy resources, such as hydropower and geothermal power. They are limited to nearby locations of waterways and geothermally active regions. However, in the case of wind, solar, and bioenergy, the geographical location does not hugely limit the usage. For instance, solar power is available more or less everywhere. This discrepancy is illustrated in Fig. 4. The figure compares the distribution of average annual solar irradiance and oil reserves. Consequently, the renewable energy sources are actually much more widely available for the majority of the population in the world.

In addition to the distribution of the primary energy sources, a considerable factor is the pace of development. In the last two decades, the cost of solar modules has dropped by an order of magnitude, and is expected to halve in the next 20 years [5]. The trend would imply that renewable energy sources will eventually become economically competitive with fossil sources. Nevertheless, the change is not projected to occur in the near future [17]. In 2050 energy production by solar photovoltaic systems is expected to have a 70% higher levelled cost than that of coal. Currently, energy produced by photovoltaic systems is more than five times more expensive. On the other hand, the levelled cost of wind power is expected to be on the same level of fossil fuel by year 2050 [17]. Hence, it is safe to assume that the transition from fossil fuel to renewables will be inevitable.

Implementation of a sustainable energy system in an urban setting requires both the minimisation of used energy as well as the maximisation of the use of renewable energy sources. Vast energy efficiency gains up to 50% could be obtained by planning of the urban environment [2]. The issues that should be taken into account include the sun's radiation, wind direction, shade from nearby buildings, ambient lighting, optimising the population density to facilitate traffic, and integration of different city functions such as work and living to minimise the need for travelling. In addition, steps toward more energy-efficient houses are needed; solutions such as passive houses that require no or very little heating can be implemented. [2]

Combined heat and power (CHP) may be produced from biomass as well as waste. By having a distributed CHP system the hot water line may be centrally heated and losses minimised. Also, the need for the transportation of the waste is minimised. Heat pumps offer a much more energy-efficient way of heating in comparison to direct electrical heating. Seawater, aquifers, or ground material may be used as a heat reservoir in order to run the heat pumps in a more efficient way. In addition, solar collectors can be installed on the buildings and seasonal thermal storage units can be built underground to utilise the heat of the summer to warm up in the winter, as well as the winter's breeze to cool down in the summer. Hence, most of the heating and cooling in future cities is taking place without or with very little electricity [2].

Solar panels could be integrated into the roof and the exteriors of buildings to produce electricity. Small-scale horizontal or vertical windmills may be integrated into buildings. Both solar and windmill parks can also be implemented outside the cities [2]. Because these energy sources are likely to be eventually more cost efficient than use of fossil fuels, the transition is mostly a matter of time. However, land-use planning needs to consider the transition at an early phase due to the long time span of the decisions.

In this section we have discussed the problems of traditional and fossil energy sources and established that renewable sources are imminently making them obsolete. In addition, we painted a view of how the overall energy palette in a future city would look. In the following sections we explore some example cities and their approaches to mitigating the problems encountered with increasing population and energy demand.

4 *The Other Side of the Eco-city Coin: Dongtan, China*

The eco-city is an existing concept within the framework of sustainable urban development, albeit still vaguely defined. There is yet no commonly accepted definition for eco-cities and eco-towns. The origin of the idea of eco-cities rests on terms like *garden city*, *green city*, *zero-emission city*, and *sustainable city*, among others, some of which were already in use at the end of the 19th century. There are torrents of positive sentiments generously expressed in the literature about eco-cities. However, the implementation of the eco-city concept does not guarantee achieving green success. It is important that both the winning and losing aspects of the eco-city concept are acknowledged and examined.

Different criteria on economic, social, and environmental qualities have been suggested regarding what constitutes an eco-city. The eco-city aims to direct the pathway toward sustainability, taking into account principles such as encouraging non-automobile transport, supporting local agriculture and community greening, prioritising land use, restoring damaged environments, promoting recycling and innovative technologies to reduce pollution and waste, and supporting ecologically sound economic activities [18]. An eco-city should minimise the use of energy, water, and other natural resources and reduce waste and pollution [19] and can be regarded as a process that delivers integrated social, economic, and environmental development [20]. The goal of this development is to further human health improvement, employment and life quality, and harmony between urban and rural areas.

Interestingly, many features of the eco-city concept relate to characteristics of traditional rural areas, such as renewable energy in the form of biomass, windmills, and watermills; proximity to nature; local production of food; and local handling of waste. Many countries, such as China, among others, have shown a great interest in the concept. But as the experience in China shows, the concept of eco-city is not yet mature and therefore not applicable to resolving the problems urbanisation has caused.

China's urban population is approximately 650 million and is estimated to reach 900 million by 2030 [18]. This makes the Chinese urban population the biggest in the world and the scale of urbanisation the biggest ever seen in human history. The heavy urbanisation process, which started only in the end of 1940s, can be divided into different phases with different governmental approaches. For decades the Chinese policy has ranged from anti-urban to town-based and controlled urbanisation. This has led to a big urban–rural disparity in terms of income levels, health care, education, and social security. In the beginning of the 21st century the government started to recognise that cities are the key to China's long-term economic growth; China needed to move toward a more self-sufficient and energy-efficient society. The eleventh Five Year Plan from 2006 points out the necessity to develop metropolitan regions and integrate strategic towns into metropolitan economies, but also to develop rural areas. Suburban towns are encouraged to grow with strong connections to their metropolitan

Fig. 5. ***A Dongtan city plan.*** *[21]*

centres. China saw the eco-city concept as a massive prospect to solve the urbanisation challenges, and several attempts to create eco-cities were started. A well-known example of this is Dongtan.

The Dongtan project started in November 2005 on the island of Chongming, at the mouth of Yangtze River and in the proximity of Shanghai, a fast-growing and very polluted megacity. There were multiple expectations of Dongtan as an eco-city [22], related to environmental protection, social and economic benefit, low ecological footprint, water and flood management, agricultural production, energy production, use and emission reduction, green city, accessibility and transport, resources, and waste management. The main goal of Dongtan was to become the first eco-city and zero-carbon city in the world, as well as to be the 'nucleus' to stimulate all future urbanisation toward eco-cities. It was expected to become a showcase for technologies and urban design to maintain economic growth and social development.

Dongtan's strategy in energy generation and conservation points out the need for renewable energy [22]. The strategy required self-sufficiency in energy with renewable sources, such as solar, wind, and biomass. The plan was to reduce energy demand by 64% with savings of 350,000 tons of CO_2 emissions, while catering for the remaining emissions via planting trees and other means to achieve a net zero emission level. There were also plans to build a CHP plant fuelled by rice husks and to produce biogas from municipal solid waste and sewage sludge. The CHP plant was to be placed in the city centre with radially outgoing pipes feeding the buildings with heat. Buildings were to be naturally ventilated and properly insulated. However, despite these explicated strategies the endeavour faded into negligence, as plans for the eco-city development were halted prematurely.

There are several reasons why the Dongtan project failed. First, it was not possible to maintain life without producing any waste. The plan was to recycle all the wastewater and solid waste. The cost to even get close to this target was too high, and was underestimated during the planning phase. Second, the planners had not considered that renewable energy production also produces emissions. As is the case of Dongtan, renewable energy production, especially in larger scale, may also have negative impacts on ecosystems. There were also local-specific problems such as the Chinese policy dictating that no agricultural land can be used for non-agricultural purpose unless an equal area of land is dedicated for agriculture as exchange. It was difficult to find a replacement for the area Dongtan was occupying. Sadly, the Dongtan 'dream' thus faded in a mere couple of years after the project was started. The goals were too ambitious, the expectations unrealistic, and the feasibility studies poorly conducted.

Nevertheless, there have also been numerous success stories of embracing the eco-city concept, in both developed and developing countries. Cities such as Stockholm, Sweden; Curitiba, Brazil; and Yokohama, Japan, are testaments to eco-city principles, achieved through sound planning and management. Stockholm has converted an old inner-city industrial area into an attractive and ecologically sustainable district. It has been able to reduce the use of non-renewable energy by 30% and water use by 41% [23]. In Yokohama, Japan's largest city, solid waste was reduced by approximately 40% with a population growth of 170,000. The waste reduction brought Yokohama savings of USD1.1 billion, which was to be used for the renewal of two waste incinerators [23]. Given the inspiration from cities like Stockholm and Yokohama, as well as the warnings inferred in the Dongtan case, it's clear that there is no one-size-fits-all solution. There are many more different dimensions than the proverbial two sides of the coin that need to be understood in integrating renewable resources with the sustainable development of cities. In the next section we continue to explore more of these dimensions in the form of semantically rich narratives of example cities in their struggles and victories.

5 Cities of Today—Energy Solutions in Urban Structures

The scale of energy demand is enormous. It is rather easy to provide electricity for a single household with an installed roof solar panel. However, if an entire city, for instance, with 5 million people needs to be powered up, the problem evolves to a new dimension. If the city is built from scratch, the eco-city principles can be easily integrated into the urban plan. However, these cases are rare at best because most cities are already bound to their locations due to natural gathering of settlements in the course of history. How do the existing cities fit into the eco-city concept? Energy solutions of urban environments are very dependent on their locations, especially when renewables come into picture. In this section we continue to explore a few example cities addressing different aspects of the energy questions in urbanisation. We now take the reader on a journey across three cities in South America and Africa: Santiago, Chile; Curitiba, Brazil; and Lagos, Nigeria. These three cities were selected because they each present a wide range of urbanisation challenges within different contexts and are suitable specimens for observing both the problems and solutions in the developing world relating to sustainability. There are undoubtedly many cities in South America and Africa that can relate directly to these examples, notwithstanding cities in other regions that can learn from the principles employed, sharing the perspectives through different levels of analogy.

We acknowledge that the chosen examples are not representative of all cities, and thus do not lend themselves to making generalisations with respect to deterministic guidelines. Nevertheless, the examples provide an enriching narrative to introduce to the reader many specific relevant issues that may be latent in the literature. Moreover, an appreciation for the complexity of the interdependence between the numerous urban planning and renewable energy issues can best be sought through storytelling.

5.1 Santiago de Chile and the Problem of Fast Urbanisation

Chile has experienced a rapid, persistent, and comprehensive process of economic growth over the past 30 to 40 years, and it has been presented as the success story in Latin America. One of the consequences of this process has been a high rate of urbanisation and urban sprawl. Currently, more than 85% of the population lives in cities. The urbanisation is very 'centralised', and in the Santiago metropolitan area alone, the population is nearly 7 million inhabitants: almost 40% of all Chileans. Santiago has a diversified economy, in which financial services are predominant. It accounts for 48% of Chilean gross domestic product (GDP), and in general it has managed to lower the rates of unemployment and poverty [24]. By 2031 the population of Santiago is estimated to increase by 1.6 million people. Santiago is a very segregated city with varying levels of family income, education, health care, housing, delinquency, and violence [25]; [24].

Santiago is situated in a valley between two chains of mountains, coastal Cordillera and the Andes in the East (Fig. 6). Fast population growth has resulted in city sprawling from the valley toward the mountains, with occupation of 50,000 hectares of previously prime agricultural land and natural vegetation covered [24]. The sprawl is still progressing up into the Andean piedmont. The sprawl of the city has caused several environmental impacts. The occupation of the agricultural land and green zones for housing not only forces food production to take place further away, but has also led to an increase of surface runoff with heavy flooding, a decrease in groundwater recharge, and polluted water sources. The air pollution has reached high levels due to

Fig. 6. ***A view of Santiago.***

many reasons; the geographical location on the bottom of a poorly ventilated valley is one. Food and commodity services, public transport, and high numbers of private cars, mainly aged, are causing emissions of particles and greenhouse gases. As a consequence of heavy air pollution in the valley area, upper-class families are escaping the polluted areas and moving to altitudes above 850 m. This is both increasing the city sprawl and deepening the differences between social classes.

Urbanisation has, no doubt, caused severe social and environmental problems. The country has set as a goal to become a developed country. This implies both achieving certain macroeconomic goals and solving social and environmental problems [27]. To achieve these goals, the country needs to have sufficient energy resources at competitive prices. The National Energy Strategy raises energy as the key element to solving environmental and social problems, in other words, to create wealth: 'The lack of access to reliable energy sources and networks constitutes a dangerous limitation to sustained social progress, to economic growth and to the well-being of the population' [26]. The main priorities are energy efficiency and the use of non-conventional renewable energy (renewable energy without large hydro power). Also, modernisation of energy is needed because old-fashioned lumber has been used for heating as houses lack central heating systems. On the other hand, The National Energy Strategy states that the use of large hydropower and energy production based on coal will be further developed. Energy use in the region has been growing rapidly. Between 1997 and 2007 the growth in energy use was 83% [27], but the growth was mainly attributed to mining and manufacturing industries. The energy system is highly privatised and practically only four companies are taking care of the whole energy business. There are also four unconnected grids. Chile has a large potential for use of a variety of renewable energy types, such as hydropower, biomass, solar energy, wind, and geothermal and wave power [28]. Developing new, renewable energy sources together with improved energy efficiency for industrial use and for use in households, commerce, services, and transportation will be the key to a sustainable future. The Santiago metropolitan region is closely related to the national energy system and relies on energy supplies from outside the region. Chile imports 90% of the fossil fuel used [28], which is a risk to the continued energy supply. On the other hand, 50% of Santiago's energy demand is covered by hydro energy, which also presents a risk to energy security in case of droughts and possible consequences of climate change.

Santiago de Chile is an example of how the geographical location of a city can have a huge impact, both in good and bad. The city is still growing at fast rates although the mountains are restricting the growth to a confined area. Moving up the hill is detrimental to the environment, but the city plan does not account for urban growth. On the other hand, the proximity of the mountains provides the city with a steady supply of hydropower as long as it keeps raining. Reduction in the use of fossil fuels is also justified with the effort to improve air quality inside the city valley. Clearly, two main strategies have to be implemented for sustainable development of Santiago metropolitan area: The first is to improve energy efficiency and the second is to increase the use of domestic renewable energy sources. Developing countries have many challenges in the journey toward becoming a welfare state, so why should renewable energy be one of their main developmental priorities? Let's turn to another South American city, Curitiba, located on the east coast of the continent.

5.2 Curitiba, the Pioneer

Curitiba (Fig. 7), with a population of 1.9 million, is the capital of the Brazilian state of Paraná; hydropower accounts for 84% of its energy consumption. Curitiba is probably the best-known case of a sustainable city that managed its own sustainable growth. The sustainability indicators of Curitiba are nothing less than impressive: The Siemens–EIU Latin America Green Cities Index gave it the highest rating for waste disposal and air quality, and the city was ranked above average with respect to water use and conservation, transport, sanitation, CO_2 emissions, and environmental governance. Carbon emissions from electricity consumption are a low 70 kg per capita, owing to the city's investment in renewables and the availability of hydropower, as well as the successful reduction of transmission losses.

In spite of a high ratio of cars per person (0.5), Curitiba had until recently coped fairly well with the traffic congestion. The city's traffic management regime includes a bus rapid transit (BRT) system that minimises use of private cars for commuting

Fig. 7. A view on Curitiba [32]

and is the envy of cities around the world. A remarkable 45% of all trips are made by bus (and 70% of commuters use bus services), 27% of trips are on foot, and just 22% are by car. Low automobile dependence and a strict air quality code have contributed to relatively clean air and nitrogen oxide levels of 23 micrograms per cubic metre, which are well below the index range of 38 micrograms in other Latin American cities. Curitiba now recycles and/or disposes of 100% of its waste, even though the average resident produces 473 kg per year. Water consumption is 150 litres a day—the average in comparator cities is 274 litres—and 93% of the population has access to sanitation [29].

Needless to say, the current greening success of Curitiba is not without its challenges and is the outcome of decades of systematic efforts. From the 1940s, with only a population of 127,000, the city expanded rapidly by absorbing migrants from rural areas and overseas, so that by the 1960s, a population of 361,000 was evident, subsequently growing to 1.8 million by 2007 [30]. The steep rise in population led to overcrowding and the emergence of squatter settlements (*favelas*), most of which developed in flooding-prone areas. The influx of industry added pollution and traffic congestion, as car ownership boomed in the 1960s [29].

The first and most vital endeavour by Curitiba was to realise the obsolescence of its previous development strategy (adopted in the 1940s) and craft a new, far-sighted Curitiba Master Plan (1965) that has provided the framework for urban development since. This new plan defined and coordinated laws to ensure continuity across electoral cycles, and an autonomous regional planning body (Instituto de Pesquisa e Planejamento

Urbano de Curitiba, or IPPUC) was set up to drive the initiatives. Neither the plan nor the IPPUC would have succeeded without the leadership and vision of a succession of mayors who governed Curitiba and mobilised political support for greening [29].

A key planning decision was to grow from the city core outward in a radial linear branching pattern, thereby opening up the city while preserving urban density and protecting green areas. This approach contrasts with the usual concentric and ad hoc development of fast-growing cities. To encourage urban growth along major axes, Curitiba invested in an integrated bus system (BRT, bus rapid transit). Land use and zoning encouraged higher density (commercial and residential) along each axis, therefore providing the density and user base that is necessary to make the system financially sustainable. The BRT is fully integrated with the land-use plan, controlling the use of private automobiles [31].

Similar principles were used by Curitiba to deal with flooding and favelas. Rather than investing in expensive drainage canals, the city set aside land for drainage and put low-lying areas off limits for development. Those areas were turned into artificial lakes to hold floodwaters, and trees were planted. A system of paths and bikes integrated the urban design. The whole strategy cost five times less than the cost of building concrete canals. Developers were allowed to transfer development rights to land in locations the city desired to preserve to land in locations the city desired to develop and provided incentives and tax breaks for the preservation of green areas as well as historic and cultural heritage sites. Slum dwellers have been relocated to safer areas, and a programme of 'social developer' has been created to use the skills of informal/illegal developers to intermediate and identify available private land that could be used for development of low-income and mixed housing units [30].

The development of Curitiba is a remarkable example of the amalgamation of technology, policy, and society. The break-away from the dependence on fossil fuels has enabled the city to implement sound green policies. These policies have in turn capitalised on new technologies to improve the development of sustainable societies while maintaining both the city's economic edge and environmental integrity. Comparatively, Curitiba has not suffered the myriad symptoms of fast-paced urbanisation through the early implementation of sustainable strategies. Although early intervention was the key in Curitiba, the success is also due to long-term commitment to a systematic strategy to develop the city as a whole. Holistic solutions are needed for large-scale problems to manage the urban growth. As we see next, for a country on its way to urbanisation, large-scale transitions in population distribution also demand a reform of the energy scheme.

5.3 Lagos in Nigeria, the Energy Giant of Africa

Many developing countries have the chance to move straight from fuel wood to electricity as the primary source of energy, neglecting the other energy transitions to coal and other fossil fuels. One of the countries undergoing such a change is Nigeria, Africa's energy giant. Despite the plentiful crude oil reserves, natural gas deposits, and renewable energy resources, Nigeria is experiencing a severe energy crisis. Most of the country's 14 generating stations are underutilised and the national grid is highly unreliable due to frequent blackouts; thus, even the 40% of the population that actually has access to electricity many times must rely on other sources of energy. Many companies have their own power-generating sets to supplement the unstable grid. In the modern world, electricity is the most desirable form of energy and the amount of electricity consumption has exhibited a positive correlation with socioeconomic improvements. The main priority of energy planning should be in implementing innovative sources of electricity for the common people. The household sector is responsible for 65% of energy usage in the Nigeria, so several energy investments should be made in this branch. As the energy demand in Nigeria is likely to increase several folds during the coming decades, the Nigerian people are in desperate need of new energy solutions [33].

A large share of electricity production in Nigeria is already accomplished with hydropower stations. In addition to that, the estimated yearly technical potential of solar energy in the country corresponds to about 26 times the recent annual electricity production. The abundance of renewable energy sources and current poor use of fossil fuels makes it feasible to centre the energy solutions on several sustainable options. The current energy programme in Nigeria has aimed to provide energy for the cities and industry. However, as Nigeria is considered to be only 50% urban [34], the rural areas should be taken into account. Generally, rural dwellers have poor access to electricity and rely heavily on fuel wood, which is the main form of energy for about 86% of rural households. The extensive use of this old-fashioned energy source has led to critical deforestation in several areas and, although renewable, it is used unsustainably, as was mentioned earlier. As domestic energy consumption is mainly for heating and cooking, fuel wood could be replaced by biogas made from waste deposits in rural areas. Also, many recent innovations promote rural and peri-urban electrification [2], which should be carried out by establishing several off-grid systems, as the national grid coverage is poor and extending it to remote areas is expensive. Solar energy technologies would be an excellent choice for household-level electricity production. By improving the conditions in rural areas, the government could slow down the migration rates and buy more time for managing urbanisation.

In urban areas the situation is more problematic, as there is simply no space for some energy solutions such as backyard biogas reactors. The former capital of Nigeria, Lagos (Fig. 8), is a chaotic example of the effect of fast urbanisation. The population of Lagos is estimated to be between 15 and 20 million and to reach 23.2 million in 2015; the city has experienced one of the fastest rates of urbanisation, with an annual population growth rate of 3.7%. The inhumane conditions in the city are best described by the fact that only 0.4% of residents have water closets at home. Urban households are relying on kerosene stoves, which are not only inefficient but also hazardous. Lagos has already taken steps toward satisfying the huge energy needs of the city by planning to build independent power producing plants (IPPs) throughout the city. By distributing

Fig. 8. A view on Lagos [35]

the electricity production to several areas, the idea is to ensure sufficient energy for the whole city. Some of the planned IPPs are thermal power stations that burn fossil fuels. Instead, building offshore windmills or solar panel fields right outside the city could bring renewable energy solutions. However, the population density in Lagos is so high that even fossil-fuel IPPs might not be enough to sustain it. There has already been a proposal for decongesting the city by building mini-satellite towns around Lagos. Each of these towns should have its own IPP to power the settlement with renewables [2]. There is, of course, the question of cost: How to fund the renewable energy investments? Well, for Nigeria, some of it could be covered by the increased export of crude oil. For other not-so-fortunate and environmentally poor countries, the technologies might still be too expensive.

The eco-city principles are useful guidelines for all urban development, but Lagos is quite far from the eco-city ideas. The megacity has grown to an extent that makes every kind of solution very laborious to implement, even with strong policy implementation. What can a city like Lagos learn from eco-cities? How do actual cities achieve the model with eco-city definition? Curitiba is an excellent example, although it took decades to reach the current state and had started making changes much earlier in its development than Lagos. Indeed, many cities desire to attain the same level of sustainable living. However, the current definitions of an eco-city provide merely principles and are hardly guidelines of how to get there. In the following section we synthesise the knowledge gained thus far, particularly from the experiences of the aforementioned example cities, and review some of our perspectives and recommendations on the future of the eco-city concept.

6 *Implementing Renewable Energy in the City Plan*

New technologies are constantly emerging to help solve cities' energy problems, but they are always implemented in the current situation, which is a city powered by fossil fuels. Instead of just adapting the energy plans, the cities should also be adapted to the renewable energy source. Renewable energy has very different demands for transport and storage, so these properties should be considered when land-use planning is undertaken. Various renewables technologies have emerged, and their availability allows governments to buy more time to prepare for the coming urbanisation. Most of the people already live in settlements that are considered to be urban. People's view of a city is an underlying factor in the decision of where they want to live, which is the main cause of people accumulating near a city's centre. The values of a population change more slowly than the world does, which is hindering the implementation of renewables in the urban environment. Next we discuss alternative views on how to rethink the urban reality and how the reshaping of a city could be conducive to accessing renewable energy.

6.1 The Layout of an Eco-city

Cities are facing two contradicting pressures. On one hand, a city should be dense enough to be efficient in the use of energy, but on the other hand, there should be space for growth and renewable energy production. Hence, the optimal urban population density is a nontrivial question. Renewable energy production requires a certain area to provide the needed power, but from the transport perspective a dense urban environment is required. Studies conducted on the trade-off suggest that in megacities such as London or Tokyo only 2% of the urban energy use could be produced locally, whereas a study on Osnabrück, Germany, showed that in low-density urban areas most of residential electricity demand could be covered by local renewables. Nevertheless, the population density of Osnabrück remains below the level that is considered necessary for public transportation systems [36]. Hence, the optimal density might lie in the range where public transportation begins to make sense (i.e., 50–100 people/ha). Nevertheless, there is a clear lack of studies in cities' potential for local energy production, as estimates were found only for rooftop-mounted solar panels. The broader picture of integrating multiple harvesting technologies into the buildings seems to be unstudied. These technologies would include rooftop windmills, wall-mounted solar panels, and district CHP solutions.

We propose that the urban area should be divided into two different zones, which have different structures and purposes. The inner zone would represent what is regarded now as the city centre: a dense, built-up area with high energy efficiency. These areas would constitute the service centres, containing most of the jobs and urban housing. The surrounding area would then be designed to support these centres. The outer zone

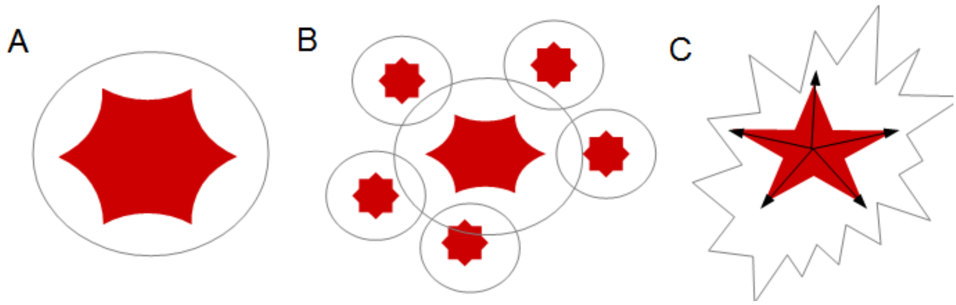

Fig. 9. ***Schematic representations showing alternative city layouts. The usual view of a city is monocentric, as in A. Other possibilities are a polycentric city with multiple dense hubs (B) or a star-like expansion of the centre in radial linear format (C). Shaded areas represent dense city centres, and the outer zone is within the limits.***

would have the space to produce renewable energy for the city's needs. Some areas would also be available for future urban growth. In this manner, each zone would be reserved for optimisation of one of the aims. These areas occur naturally in every city, but their characteristics and relations differ significantly from one place to another. But exactly how should the zones be defined and distributed to obtain the energy-optimal city?

The current problem seems to be that cities are monocentric and the dense area in the heart of the city expands uncontrollably outward. The energy solutions might not be adequate to sustain the growth. Often the areas in the vicinity are already full of settlements and the distance between energy production and consumption starts to increase, which makes the availability of energy even more problematic. Expansion is likely to occur on the edge of the inner and outer zones. By increasing the ratio of outer to inner zones, the cities can create more buffers for growth. We extracted two ways to do so, as shown in Fig. 9. One strategy, which has been proposed for Lagos in Nigeria, is the establishment of small satellite cities around the centre, the polycentric approach (Fig. 9B). Each of these minisatellites would have a dense centre corresponding to an energy-efficient inner zone. The centres would each have their own energy solutions, making them self-sufficient because the surrounding area could provide the space needed for solar panel fields, windmills, or CHP plants. Of course, the exact energy source is defined by the availability of the energy sources in, or in the vicinity of, the city. By dispersing the city's inner zone, it would be possible to release some of the growth pressure of the main centre and expand the possible city area with better management. The network of hubs should be connected with efficient public transportation solutions. Within the hubs it is ideal that all the elements needed for living, including working places, are reachable by foot. Hence, the need for commuting is minimised.

Another possibility to de-densify the city centre would be the plan adopted in Curitiba. The core of the city is expanded outward in a linear branching pattern, where each branch serves as a local centre. This star-like model (Fig. 9C) also creates a suitable blueprint for the transportation system, having routes catering for each branch. The transportation of energy would occur through the same axes, and a production centre would be placed at the end of each branch. The structures presented in Fig. 9 are of course very dynamic and inter-convertible. The first step is to identify the current structure and problems of each city and then make decisions toward the alternative structures.

Having defined the two functional areas, we can now turn back to the question of population density. As mentioned earlier, it is interesting that urban population density, measured as persons per hectare, is the highest in areas that are still undergoing urbanisation. The density also decreases with increasing income, correlating with higher consumption [12]. The main problem with high density is associated with the monocentric city view (Fig. 9A), as is displayed by Lagos city. Although the average population density of Lagos is only a moderate 120 persons/ha, the problems are mainly due to the centralisation of population pressure that occurs in the Lagos Island [7]. With a distributed city centre, the inner zones or service hubs can reach high values of density to maximise energy efficiency. A potential value would be 150 persons/ha, which is the estimated average density in built-up areas in Southeast and Central Asia [12]. The outer zone could have an average of 50 person/ha to make the public transport connection between the hubs sensible to support. Of course, important parameters to measure include the size of each hub and the distances between them. All of these factors then point to the fundamental ratio of how much outer zone is needed to support each energy-consuming centre. This estimation should be the starting point for urban planning. High population density also relates to the intensity of energy use, and thus energy production capacity is a determinant factor in the design of the supporting outer zone.

Renewable energy sources such as solar and wind power pose critical choices of either centralised or decentralised production. Centralised energy production would need huge space and investment. Similarly, distributed production has its own obstacles in terms of commitment to be fulfilled by individuals, as it requires critical mass to be successful. In such circumstances, cities need to have a solution model that can leverage the benefits of each strategy. In our concept of a future city we propose a mixed model of a linked distributed energy system with few centralised energy units and multiple small to medium-sized energy production centres that are linked with each other and complemented by the distributed production from individual buildings. The individual production sites also need to be linked to the main chain of distributed centres. This mixed model of distributed energy production units can be efficient, more reliable and capable of fulfilling larger demands compared to either strategy alone.

City councils should focus on developing a self-sustaining community around the population hubs. We envision these communities to be self-fulfilling in terms of employment and services needed. Business and job creation are the central issues in creating such distributed city centres. City councils should devise a policy that would encourage businesses to distribute across these centres. Providing businesses and industries with incentives to be located in the desired centres would ensure the development of such centres.

6.2 The Road to Atonement

To complement our recommendation of an ideal eco-city layout and the nature of the corresponding renewable energy production, the core question to address in this study is how to get there. What are the considerations that need to be taken, for instance, as a decision maker or any custodian of eco-city development? This study aims to give the reader a down-to-earth perspective on how an eco-city can be brought about by emphasising factors identified in the cases covered and recapitulating them with semantically rich references to the circumstances. That being said, it needs to be borne in mind once again that there is no one-size-fits-all recipe or checklist. The solution is more of an art than science, and more akin to complex relationships of causality puzzles, which rely on the capacity of the eco-city champion to reason and execute.

One piece of the puzzle toward the future eco-city lies in the national energy policy. It is important that such policy emphasises production and growth of the renewable energy market. Feed-in tariffs are examples of such policy measures that have been put in practice to promote renewable energy. A feed-in tariff guarantees profitable renewable energy production by guaranteeing a fixed price for electricity production. The main objective is to support the development of technology at various stages of the technology maturity cycle [37]. In the past, countries like Germany and Denmark have successfully implemented such policies in the context of renewable energy development [38]. For the initialisation of renewable energy market development, feed-in tariffs can play an important role.

Renewable portfolio standards (or renewable obligations) are another alternative to support the initial market development of renewable energy. These mandate that electricity suppliers must source a certain proportion of electricity from renewable sources [39]. Both feed-in tariffs and renewable portfolio standards are two alternative policies that differ on the question of where to place the political control and market control—on the price, as in feed-in tariffs, or on the supplier side, as in renewable portfolio standards [40]. Protective policy measures as such ensure that the market of renewable energy is created and protected.

Energy policy devised around financial incentives, a carrot-and-stick-based approach, has the potential to yield success in implementing renewable energy resources. It increases the market penetration and usage of renewable energy and penalises the usages of fossil fuels, and thus, is capable of creating conducive environment for the growth of the renewable energy market. For example, Sweden has successfully implemented financial incentives combined with taxation based on CO_2 emissions. Tax reliefs for biofuel have created a suitable environment for the growth of the bioenergy (mainly heat fuel) market [41].

When a nation implements policies and commits the resources for the development of a renewable energy market, it sets the long-term path for the future. However, as a precursor to decisions on policies, a more fundamental change in mentality is required to properly justify the implementation of such policies. This step is often neglected, resulting in the impotence of such policies in the long term. This leads us to another piece of the puzzle that goes hand in hand with incentive policies, although on a slightly more fundamental level: governance.

Governance played a central role in Curitiba, for instance. Curitiba's first step on the path of sustainable development was by virtue of its local leaders, who acknowledged the antiquated nature of the city's previous development plan. This set into motion a series of that resulted in a new Curitiba Master Plan. With this plan, the ensuing developmental policies could be properly justified and even tailored over time to remain meaningful with respect to the proven results of the studies involved in the master plan. To facilitate the compilation of such a long-term plan, local municipal leaders played a crucial role in ensuring the integrity of the initiative. They were wise to foresee the potential effects of election cycles, and thus actively set up an autonomous committee to champion these green goals, unaffected by the possible bias of bureaucracy. This allows for enough objective authority to represent sustainable development interests in government, independent of the ruling local party—an intervention desperately needed in many developing cities.

On the topic of politics, another added motivation for the adoption of renewable sources is the potential to be energy independent. For instance, Chile imports 90% of the fossil fuels used, which creates an additional level of political and economic pressure. The default nature of fossil fuels (being limited to specific locations) has imposed this dependency, which can well be liberated through the adoption of renewable sources available locally. As part of setting up any master plan, the local conditions need to be well studied. Renewable energy sources are geographically distributed and abundant. Good feasibility analysis is a crucial requirement to assess the local conditions and constraints, as well as the impact that any renewable energy production will have.

Both Nigeria and Santiago have an abundance of renewable sources, which are overly underutilised. Of course, they are also blessed with hydro-electricity capacity, as is Curitiba. However, positive aspects may also have negative implications and vice versa. The mountains surrounding Santiago, providing good catchment areas for hydropower, also impose limitations on the development area. The city sprawl is a much bigger problem in Santiago, as the areas around the mountains are even more ecologically sensitive and require stricter regulations for environmental protection, and at the same time such sprawl leads to a higher density of the urban population enduring many of the urbanisation problems mentioned earlier. All of these types of constraints and their interrelationships need to be well understood before policies are even put into place.

Dongtan poses an example of a failure due to poor leadership and planning. Notwithstanding the possibility of corruption-driven activities in local governments, there were explicit incompetencies that can be identified and hopefully avoided in future by other cities. In Dongtan it was evident that studies were poorly done and the impacts of the greening activities were not understood. For instance, the goal to recycle all the wastewater and solid waste was grossly underestimated financially. A proper cost-benefit assessment is crucial if such problems are to be avoided. Another aspect overlooked was the CO_2 emissions created by the renewable energy solutions themselves. At the scale in which the system was to be implemented in Dongtan, the emissions nonetheless had an adverse effect on the ecosystem, regardless of the new energy solution. This shows a poor understanding of the envisioned solution, and perhaps is caused by a poor understanding of the problem as a precursor. The usage of the land areas designated for specific development, and the related policies, was also a major problem for the project. Many of the problems mentioned earlier were revealed late in the Dongtan project after execution had already begun, leaving managers no choice but to abandon an incomplete project, as it was not financially viable to continue. There may be hope for Dongtan in the future to fulfil the original dreams of a purely zero-emission eco-city, provided that the due price is paid to rectify these mistakes. Nevertheless, this case highlights the interdependence of policy, technology, and finances in the decision framework for eco-cities, and the importance of sound leadership to drive the required studies and pose the necessary questions well in advance of the beginning phases of such initiatives.

On the issue of land use and manipulating urban layouts, tax breaks can be given to landowners for the preservation of their green lands in certain areas, which was the case in Curitiba. Other incentive programmes can be used to encourage the conglomeration of development at certain demarcations, for instance, discounting property prices or energy prices, be it for residential or commercial purposes. These endeavours need to complement a 'pro-public-transport' approach of city layout such as, applying the star-like development scheme mentioned previously to accommodate the transit needs of new residences and business units. For Curitiba, this has worked well, with the city integrating transport routes with each point of the 'star' of the urban layout. With this approach, multifunctional urban planning approaches can be implemented to suit the layout. For instance, parking lots could be shared between different establishments to cater to needs at different times; or, as in Curitiba, parklands can double as flooding zones so the construction of specialised canals is not required. Once again, the roles of the municipal leaders are of utmost importance.

Speaking of the role of local community leaders, much work also needs to be invested in creating public awareness about the benefits of new initiatives, and to encourage public support for the endeavours. In many cases, energy-efficiency issues may be improved through behavioural changes, such as achieving waste reduction through recycling or encouraging the use of public transport instead of cars.

7 Conclusions

The future world will be more urbanised than before. With this growth and development the world will need more energy than ever. The major source of world energy, at present, lies in the fossil fuels. The world cannot afford to rely on fossil fuels forever. The longevity of renewable energy combined with its minimised adverse environmental effects offer attractive energy outlets for any economy. Generation of energy from renewable resources needs to be integrated into the urban way of life and consumption. As one can see, there are many ways to put together the puzzle on the path to a future eco-city. Each piece of the solution includes many dimensions that relate to one another in often-unquantifiable ways. Causalities between different aspects of considerations need to be well acknowledged, particularly given the tacit nature of the knowledge in the field. Once again, there are no recipes or steps of checklists to follow.

Winston Churchill said: ‘We shape our buildings, afterwards our buildings shape us’. It is easy to build a different kind of settlement, but changing the mentality of people about their surroundings is the real challenge. We need to start rethinking our cities according to the future with renewable energy sources, and not linger in the past. Up-to-date settlements will then reshape us toward sustainable energy.

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How Can We Change the Everyday Energy Consumption Patterns of Citizens?

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Abstract. The state of our energy production system is changing. The pressure to reduce the use of polluting fossil fuels grows more severe and simultaneously the responsiveness of the electricity production system to electricity demand is hindered. This paper discusses different methods of engaging electricity consumers to change their consumption patterns to even out peaks in demand or to better align them with possible peaks in electricity production. In particular, we take the Kalasatama district of Helsinki as a case study example. We focus on analysing the views of its residents on their energy consumption patterns. Additionally, the views of Helsingin Energia, a large electricity and heating company, and Forum Virium, a city developer organisation, are discussed. Based on our empirical research, guidelines on how to best engage consumers are drawn and a practical solution example utilising gamification and ICT is presented.

Keywords: gamification, ICT, demand flexibility, domestic energy consumption, electricity user behavior

1 Introduction

With the increasing concern over climate change, the pressure to reduce the carbon dioxide (CO_2) emissions caused by energy use grows more severe. Because rapid changes in energy demand have been mainly supplied by the use of natural gas and coal, reductions in the use of these fossil fuel–based sources affect the flexibility of our energy production system. As a result, flexibility needs to be transferred from the energy production side to the energy use side.

Previously, transitions in the energy sector have lasted long to unfold and have resulted in an increase in energy consumption [1]. The nature of the change sought in this article is inherently different. It requires the elements included in the last transitions as described by Fouquet [1]—namely, the successful penetration of new energy sources, technologies, and institutions as well as the decline of others—and places a major role on the demand and consumer side. However, we are after a change in which the role of consumption is not to increase. Rather, we are looking for ways in which energy use would move toward more flexible consumption patterns in which energy would be used in those times of the day when the production of renewable energies is the highest.

Our article is based on the realisation that demand flexibility cannot happen without the active involvement of and strong support from electricity consumers. Consequently, we focus on discussing the different methods of engaging electricity consumers to work toward the goal of flexible energy use. This includes both making them more aware of their energy consumption patterns as well as motivating and enabling them to change. This paper discusses two larger trends that can affect consumer behavior: (1) The ever-faster developing information and communications technology (ICT) industry can be used to make users more aware of their consumption behavior and (2) with the help of public policies, users can be encouraged or even forced to change their behavior.

1.1 Motivation: The Benefits of Increased Flexibility

Renewable energy sources, such as wind and solar power, are fundamentally different than conventional energy sources because their production capacity at each given moment is determined by forces of nature. This requires a different approach to energy usage as a whole. In the future scenario dreamed by many, where a major share of electricity is produced by these sources, electricity production cannot be so easily ramped up and down with electricity demand.

As a case example, the electricity production and spot prices of Germany in week 33 in 2014 are displayed in Figure 1. Germany has been ramping up its solar and wind production since 2000, and in 2013 these corresponded to 7.8% and 4.5%, respectively, of the total electricity production of Germany [2]. The effect of both wind and solar can be seen distinctly in Figure 1.

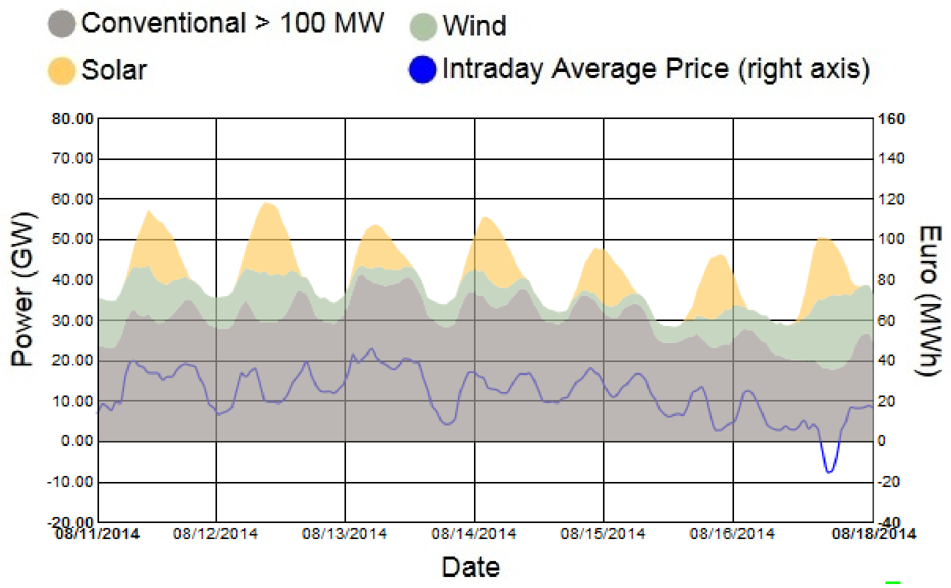

Fig. 1. ***Electricity production and spot prices in week 33, 2014, in Germany [4]***

Solar electricity is only produced when the sun shines. On a reasonably cloudless August day in Germany, this means that the electricity production starts around 7 AM and ends around 7 PM, reaching its maximum around 2 PM. Fortunately, the energy demand experiences a corresponding increase. Nevertheless, it often occurs that the increase in the solar energy input is larger. This happened, for example, on August 12, 2014. This results in a reduction in conventionally produced energy. In the case of Germany, this results in the shutdown of the most expensive conventional power plants, which are typically gas or coal powered, which incurs a lower electricity price.

On days with high solar and wind electricity production and low demand, such as August 16, 2014, it can happen that the ramp-up in renewable production is particularly rapid. On these days, the operators of conventional power plants sometimes choose to pay the electricity users to use their electricity in order to avoid the shutdown of their plants, which is a costly operation in itself. This results in a negative electricity price [3]. These kinds of price fluctuations are of course highly undesirable from the perspective of the electricity producer. In addition to the direct loss of capital, it makes the task of predicting future electricity prices challenging.

For operators of conventional power plants, this issue reduces their profits but it is not insurmountable: They can still profitably operate during those hours when renewable electricity generation is low. But for the productivity of renewables, the situation is dire, because these hours when the electricity prices are reduced are the hours when the most renewable electricity is produced. If the electricity price is low during these hours, the competitiveness of renewable energy sources suffers. This lowers the attraction to invest in new renewables.

A potential solution for this problem is to increase the flexibility of electricity demand, or, in other words, to try to focus energy consumption on the hours during which there is a lot of renewable electricity production.

1.2 Benefits of Flexibility in Finland

Finland does not currently have a similarly high capacity of renewable electricity production as Germany. However, increased demand flexibility would ease the transition toward a society with a larger renewable energy production base. Additionally, nuclear power, which covers about one-third of the electricity production of Finland [5], is a reasonably inflexible form of electricity production. Demand flexibility can also be used to even out demand peaks and thus make the electricity distribution system more stable. Electricity consumers could also benefit from this, as the demand peaks considerably raise electricity prices. Figure 2 shows the hourly electricity consumption and market price in Finland on February 5, 2012. This was a particularly cold day [6], which typically induces an electricity demand peak in the evenings due to the increased need for heating. It can be seen that the electricity price remains stable at around 40€ when the consumption stays below 12 800 kWh per hour, but then when consumption increases, the price starts to increase proportionally to the consumption, reaching a peak price of approximately 60€, which is around 50% more than the 'base' price. Thus, if part of the electricity consumption during this peak could be consumed at another time of day, the electricity price would remain stable and considerable savings could be made.

1.3 Research Design

In this article we take a socio-technological approach to exploring the possibility of *user behavioral change to achieve flexible energy consumption*. Our motivation is that if the consumption of environmentally sustainable resources, such as wind and solar energy, continues to increase, a change in conventional social habits is unavoidable. If a habitual change is needed, there must be incentives driving people to change.

As the European Energy Agency states [9]: '… technical interventions alone have lower impact and are more expensive to implement if carried out in isolation, i.e. without any accompanying programme designed to encourage behavioral change'. Accordingly, we understand that technology alone is not able to encourage behavioral change. Therefore, a societal perspective is important to dissect the social factors influencing individual behavior. Second, according to Shove's study [10], if policies are enhanced and targeted to achieve a *collective* behavior change, they can promote persistent and sustainable habits. Shove suggests that the process of looking into micro (individual), meso (community), and macro (system) levels is important for seeing the relations between individual reasoning and collective practices, and the formation of a socio-technical landscape for a new social order. Based on these two fundamentals,

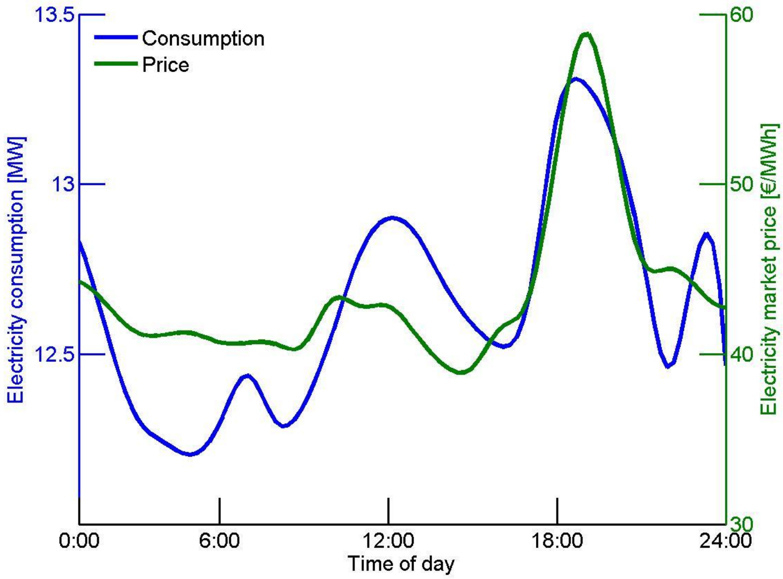

Fig. 2. ***Hourly electricity consumption and market price in Finland, February 5, 2012. Consumption data from [7] and price data from [8].***

we took the people and community study approach from a societal perspective in order to explore the possibility of promoting a sustainable behavioral change in energy consumption.

Within the framework of promoting energy efficiency in a city, we identified the energy provider, the energy consumer, and the city itself as key actors. A city plan on energy strategy will shape the behaviors of its citizens concerning energy demand and use; and, on the other hand, the long-term behaviors of citizens will influence the energy plan of the authorities. These interactive relations occur in a constructing and reconstructing manner, forming the behavioral trend in a society. Therefore, the identification and study of the key actors allow us to explore the dynamics and intensity of the interaction between the two; and, from the findings, to see a possible way to affect a wider range of actors to establish sustainable habits for the ultimate goal of energy efficiency.

Our main data come from user research in which we interviewed and observed people living in Kalasatama, forming the core of our study. Altogether, four interviews were made, including two home visits. The surveys were done twice, once in October and once in November. In addition, one of the authors living in Kalasatama also made observational studies in the area.

We also interviewed Veera Mustonen, a project manager at Forum Virium. The meeting helped us to have an idea of the overall strategic planning, foresights, and forecasts of the smart communities in Helsinki. At the same time, the interview gave us deeper information on the background of our field site. We also interviewed Atte Kallio, who works as a project director for Helsingin Energia and is responsible for Kalasatama's smart energy systems project.

2 Catalysts to Change

2.1 Framework Defined by Policies and Regulation

Energy consumption patterns depend on individual choices, but policies can influence these by supporting the desired consumption patterns or making the unwanted consumption habits less desirable. In this section, we present the political framework through which energy and energy demand is being regulated in the context of our case studies.

Energy is an important resource that contributes to both the economic growth of a region as well as the welfare of its citizens. Thus, all energy forms are regulated in some way [11]. Political interests in energy issues have been affected by the threat of climate change. This has led to demands to reduce the use of fossil fuels, a major source of CO_2 emissions. Both the EU-level and national policies of the Member States emphasise the need to reduce the greenhouse gases (GHGs) resulting from energy production.

Researchers have underlined the importance of government intervention in transforming the energy sector in a more sustainable direction [12, 13]. At the EU level, a binding target has been set to reduce the GHG emissions at least 40% below the 1990 level by 2030. Within this target, the use of renewable energy has been announced to play a key role to ensure 'a competitive, secure and sustainable energy system'. A goal to increase the share of renewable energy in total energy consumption is set to be at least 27% by 2030. This is a binding target at the EU level [14]. In Finland, the use of renewable energy is predicted to amount to 38% in 2020 with current actions [15].

Energy end-use efficiency and energy services were called for at the EU level through informative billing and other types of feedback in order to enhance consumers' awareness of their electricity use [16]. In the Energy Efficiency Directive [17] these were further promoted by requirements to:

- Introduce smart metering where proven feasible and financially cost-effective.
- Base energy billing on real consumption and provide complementary information on historical energy consumption.
- Encourage Member States to ensure that national energy regulators implement demand-response programmes.

The issue of energy flexibility was directly tackled in the EU Commission staff working document on 'incorporating demand side flexibility, in particular demand response, in electricity markets' [18]. This document notes that energy flexibility could help to deliver cheaper electricity to consumers and enable greater usage of renewable energy sources. The Commission takes the stand that market-based approaches should be used to increase the demand-side flexibility. It notes that demand-side flexibility needs 'an internal energy market that treats demand-side participation fairly in comparison with supply and that is equipped with a smart infrastructure system, opening up new possibilities for participation' [18, p. 7]. The Commission puts strong emphasis on the role of market actors, but also recognises the need for regulative action. It notes that the current EU directives already make demand response possible, but that Member States need to transpose the directives effectively to make them reality.

In practice, there are challenges to make this demand-side flexibility a reality, as demonstrated by Germany's example presented earlier. One source of this problem has been the used energy subsidy schemes, where the most favored form of support has been the feed-in tariff [19]. The feed-in tariff promises a certain minimum price for every kWh produced by renewable methods. Although this makes it easier to predict the price and thus the profit obtainable from renewable electricity, it decreases the incentive for the renewable energy producers to come up with solutions for the flexibility problem. A more suitable form of support, then, would be the feed-in premium, where a certain amount of money is given to the producer on top of the electricity market price [20]. Fortunately, this has been noted by legislators and proper action has been taken [21].

In addition to changing the legislation on energy production, another approach is that policies could (and in our opinion should) also motivate citizens to change their consumption patterns. Research on motivations to make energy use more flexible is scarce, but studies have investigated the question of how to motivate energy savings or energy efficiency and how policies concerning these issues should be formulated. Findings indicate that single actions should be avoided and a problem diagnosis should be done before engaging in any intervention to be able to target behavior [22]. Frequent feedback with appliance-specific breakdown has also been found essential [23]. The importance of accompanying technological and economic measures with an understanding of the social and cultural changes has been underlined [24]. As stated in section 1.3, there exists some proof that policies aimed at collective behavior change will have more pertinent effects [1].

In the context of our case studies, the relevant legislation comes from the EU level as well as national and city levels. In 2008, a working group of the Ministry of Employment and Economy in Finland published a report on actions to develop electricity demand response. The main result was the introduction of smart meters. However, the report stated that the small consumers, mainly households, do not have any major role in demand flexibility, and the major effect of the introduction of the smart meters would be that consumers would get more accurate information on their consumption. This could encourage energy-efficient and energy-saving measures. [24, 25]

At the city level, in 2010 the city of Helsinki accepted the aim to increase the share of renewable energy production to 20% by 2020 and develop the electricity and heating production of Helsingin Energia toward carbon neutrality [26]. Although there are some plans to integrate smart metering with other smart applications in some of the new areas that are being built, no clear objectives regarding energy demand flexibility have been raised in the city council.

2.2 Role of ICT in Energy-Efficient User Behavior and Changing Consumption Patterns

Household energy consumption has increased substantially and is a major contributor to overall energy consumption [27]. In this section, we focus on opportunities presented by ICT in achieving energy efficiency from users' and households' perspective.

Technology has evolved significantly over the years, and nowadays we have many available energy-optimised appliances and systems. These are essential for achieving savings and will have a major impact on the demand for energy. The big question still remains, however: Are the users ready to change their behaviors and adapt to the changes? The answer is complex and not straightforward. The issue is not just technical; social and behavioral aspects are included as well. Nonetheless, ICT can play a significant role in minimising the gap between users and their energy-related decisions by making energy consumption information more visible and real-time available.

It is a matter of debate whether ICT is helping to reduce energy consumption. On the one hand, it can increase the efficiency of systems and services. However, it can also affect the energy-efficiency numbers negatively by establishing an ever-increasing number of power-hungry data centres. Laitner et al. estimate that in recent years, for each kilowatt of energy used by ICT equipment, approximately 10 kilowatts is saved through productivity gains and efficiency improvements [28]. The debate is fueled even more by scenarios in which ICT helps to reduce commuting by introducing teleconferencing or by introducing e-mail as opposed to conventional mail and thus helps to make savings in overall energy consumption. According to a report published by Intellect in March 2011 [29], using smart ICT tools in daily activities makes it possible to reduce global emissions by 15%. The possible savings are much bigger than the global footprint of ICT, which is 2%. Thus, ICT is an important driver and an essential enabler for an energy-efficient future society.

User awareness about energy efficiency is increasing, and as the technology advances we predict that in the future it is going to grow further. With the proliferation of the Internet, social media, and global connectivity, it is possible for ICT to influence the decisions of users in all areas of their personal lives—from buying energy-efficient white goods, to installing smart meters and sensors in their homes, to making energy-efficient decisions about their daily lifestyle routines.

The major challenge in this regard is how to make information more visible in a simple and understandable way. For example, there are many situations in which people have positive intentions of reducing energy consumption or choosing green options when purchasing white goods or electricity. Still, they do not take even the simplest measures to reduce their energy demand. A majority of the world's population gets their energy-consumption data on a monthly bill and the quantities they look at are the consumed units of electricity for that month and the money they have to pay for those units. ICT can enable users to visualise energy consumption data in a more presentable and fine-grained way so that the users are more concerned about their energy consumption. In addition, with ICT it is also possible to motivate users to reduce their consumption either by using a social context or a personal goal-based context.

In a different context, we can also consider the example of the automated power-saving features that most of our laptops and workstations have. Although the option for saving is there, all too often users are reluctant to use or unaware of how to use such features, either in a home or office environment. All of these issues present an opportunity for ICT to play a major role in enabling users to reduce their energy consumption and get involved in energy-efficient practices.

2.2.1 Research Trends

As presented in the previous section, although there are potential opportunities for energy savings, end users are generally less motivated to save energy, less informed about their energy consumption patterns, and less literate about the energy-saving features of their equipment and devices. Keeping all these deficiencies in mind, substantial research efforts have focused on profiling user behavior for potential areas of improvement, enabling in-home smart technologies for real-time energy data communication, and using machine-to-machine and human-to-machine communication paradigms for improving the energy consumption experience of users and enabling them to make smart decisions related to energy.

Barbato et al. [30] present architecture for intelligent user behavior profiling and automatic system calibration with real-time data using wireless sensor networks (WSNs). They have used WSN to monitor physical parameters such as user presence, light, and temperature. This architecture makes use of MobiWSN middle-ware, which enables home automation systems to interact with the WSN. Once the aforementioned data are gathered, different profiles are created for lighting, temperature, and user presence. Profiling is performed in both off-line and real-time mode. In a real-time scenario, profiling data are analysed to make smart decisions—for example, regulating the lighting system according to the level of natural light from windows, controlling the heating/air-conditioning system to set the temperature in the rooms according to the user profile, and so forth. Although the system is self-adaptive and automated in most scenarios, user involvement in decision making is rather limited, and as a consequence it might demotivate users from using it.

Mattern et al. have compiled an interesting set of measures [31] for inducing behavioral changes, which are categorised in two groups: rational behavior, which incorporates informational support, and irrational behavior, which constitutes motivational and social positioning measures. Informational support is concerned with presenting the consumption data to the end user in an understandable and comparative way. It is of no debate that presenting consumption data in mere kilowatts or other technical terms is of little help for the majority of the user base. Information should be presented in a simple and understandable way to be adequate for most of the users. Comparative consumption data using other nearby households or families are also useful for a user to perceive his or her own rank among others with similar consumption patterns, whereas the motivational measures are more about instilling energy-efficient decisions in users' thinking processes. Examples of such measures are goal-setting, energy budgets, and social comparisons. Goal-setting measures help people to set individual goals and can deliver continuous feedback on the current state of consumption and may provide suggestions on ways to improve the consumption pattern to achieve the initial objective or goal.

Measures based on an energy budget motivate the user to conserve more and spend less in order to be within the energy budget at the end of the month, which was set at the beginning of the month. Energy budgets can also be set for daily consumption scenarios. In fact, a British pilot project suggests that with pre-paid electricity tariffs, a method of energy budget–based monitoring proved to be influential and resulted in substantial saving efforts [32].

Mattern et al. [31] proposed an eMeter system, which connects a smart electricity meter with a mobile phone application. This simplistic approach tries to realise promising energy usage feedback features in its system. The eMeter system has three independent components: a smart electricity meter that monitors the total domestic consumption, a gateway that manages and gives access to the logged measurement data, and a portable user interface on a mobile phone that provides real-time feedback on energy consumption. The interface enables users to interactively monitor, measure, and compare their energy consumption with the granularity of device-level data. Figures 3 and 4 present the overall architecture and different user interfaces of the system.

Bonino et al. have performed a thorough investigation and analysis of the capability of a smart home to automatically and timely inform its inhabitants about their energy consumption. With the results of their survey on over a thousand participants, they also analysed and formulated an understanding of what feedback is felt by home inhabitants to be easier to understand, more likely to be used, and more effective in promoting

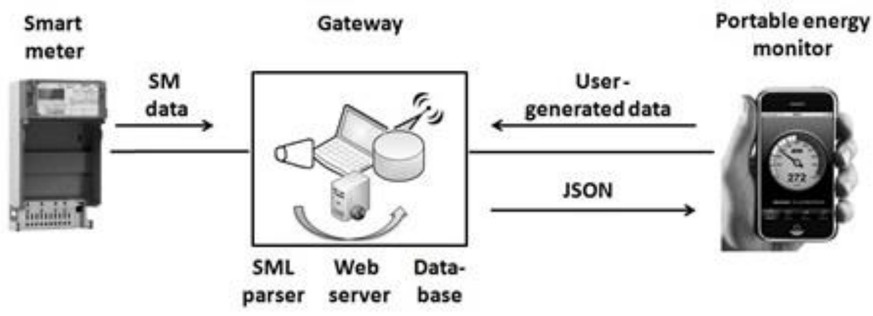

Fig. 3. ***Smart meter communicating with the mobile UI [31]***

Fig. 4. ***eMeter user interface** (left to right)**: current consumption view, history view (cumulative consumption), history view (budgeting), device inventory view, measurement view [31]***

behavior changes. In addition, they have harvested user opinions on energy feedback interfaces [27]. This research also introduces the concept of different measures like Mattern et al. [31]; Bonino et al. [27] categorise energy-saving strategies as measures based on information, goal-setting, or commitment, and they have used feedback-, reward-, and criticism-based approaches to inform users about their consumption patterns.

Bonino et al.'s [27] visualisation layout as shown in Figure 5 is both appealing and sensible, as they have used colour-based real-time consumption visualisation to display the data. As the energy consumption of any particular room changes, the subsequent colours also reflect the change—for example, a change from green to red informs the user that the consumption in that particular room is higher than normal. This research concludes that most users are interested in having such interactive home displays (IHDs) in their homes and that the goal-based feedback systems are indeed useful.

Although a good amount of research has focused on which type of information is more effective and user-friendly, few scholars have actually involved the end users

Fig. 5. ***Visualisation layout [27]***

in this process and asked which type of energy consumption information would be useful and effective for them to visualise the energy-use scenario and conserve energy. Sami Karjalainen presented interesting research in this regard in 2011 [33]. In this paper, the author first developed eight different prototypes that constituted different ways of presenting electricity consumption feedback. While building the prototype, systematical analysis was performed on different types of feedback methods and the prototypes were carefully designed, as claimed by the author. The consumers were shown the prototypes and interviewed regarding their ranking of the prototypes and what they would like to see in addition. The results from this research suggest that consumers would like to see the following features/data in the feedback: energy consumption cost over a period of time, appliance-specific breakdown of consumption, and historical comparison (i.e., comparison with their own prior consumption). The prototypes are presented in Figure 6.

In addition to these trends in devices that allow users to get instantaneous feedback about their daily consumption patterns, a significant amount of research is also focused on home automation systems, which are aimed at making the daily lives of users more efficient. The Internet of Things (IoT) or machine-to-machine communication (M2M) allows communication between entities of any kind. Houses and buildings deployed with sensors would allow the use of devices with communication technologies that are able to identify and communicate with each other. Users may enjoy a totally new and energy-efficient environment without needing to worry or think about consumption patterns.

An example is a smart house that is equipped with automation tools and sensors. Suppose, for example, that the windows have smart blinds that can communicate with the electrical lights and bulbs and lessen their intensity or switch them off totally based on the natural light sensed from the environment. In addition, sensors inside a room can automatically detect the presence of people inside the room and switch the lights on and off automatically. With the help of smart phones, it is possible to operate the home's cooling or heating system remotely. A smart TV may adjust its brightness or switch on and off based on the presence of viewers or on their attention toward the monitor. GhaffarianHoseini et al. [34] present a number of such examples, which were developed as pilot projects in different universities and show the wide range of possibilities that a home automation system can offer. These methods can provide many plausible solutions for a sustainable, energy-efficient society of the future.

2.3 A Possible Tool: Gamification

The term *gamification* originated in the digital media industry and is relatively new; however, the concept of gamification is not. Although the majority of the current examples of gamification are digital, the term should not be limited to digital technology [35, 36].

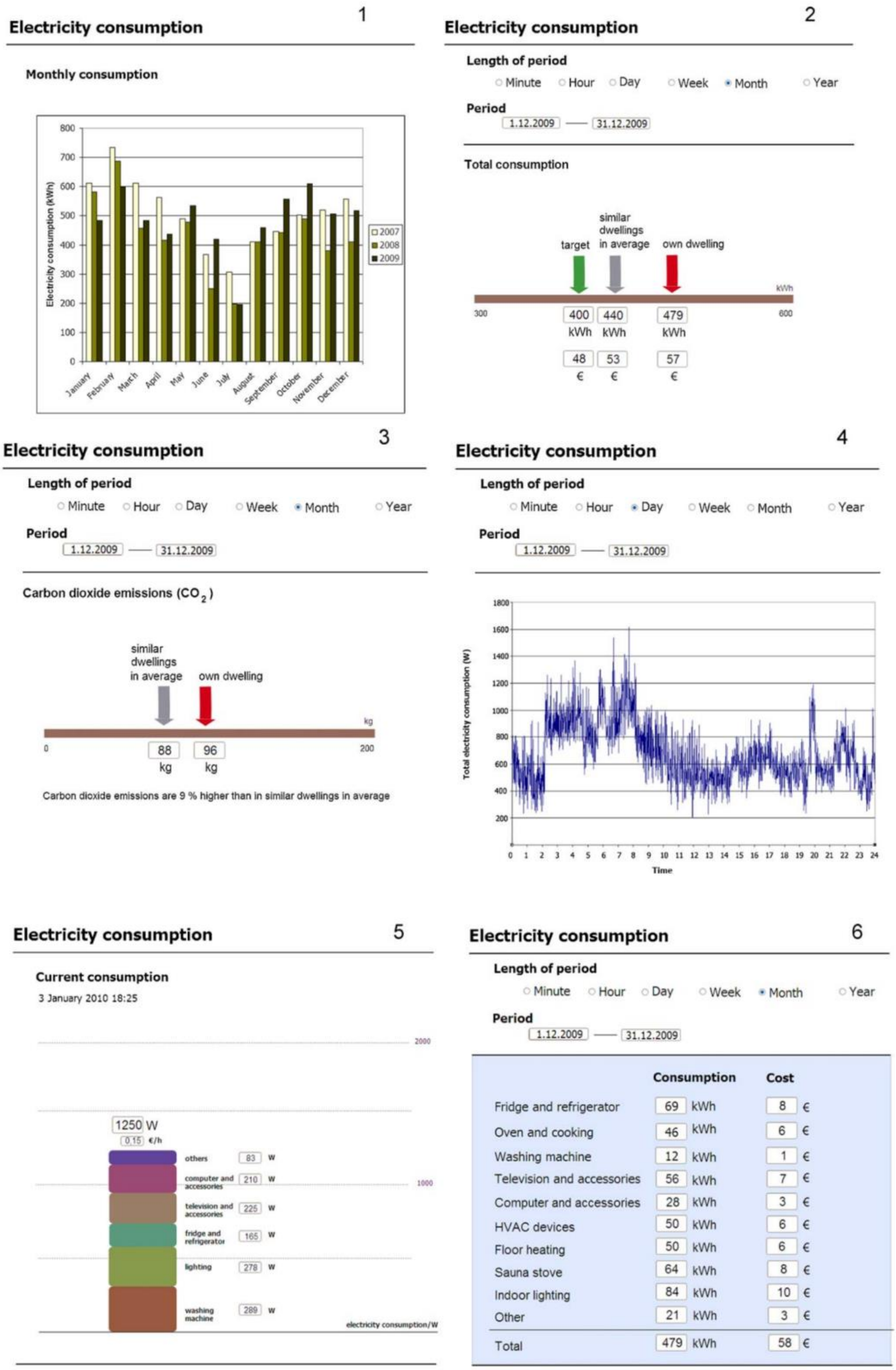

Fig. 6. *User interface prototypes [33]*

People can be engaged and motivated in various ways to achieve their goals. One way is to use gamification, which is the concept of applying game mechanics and game design techniques. There has been a long history of using fun and play to motivate people and make work seem more enjoyable. The role of playful behavior and playful thought in human development is positive. It is said that particularly the unstructured, spontaneous game is a powerful force in human development. It gives us courage and instilled confidence. There are at least two kind of play: playful play and productive play. Playful play is doing activity for the pure joy of doing, such as skipping rocks on a pond's surface or playing air guitar. Productive play has a specific purpose, such as to produce a tangible thing like a widget or to win a tournament, rather than fun. Productive play can be weaved into work or it can be actual work itself.

Games are considered to be an escape from the 'real world'. In computer games, for example, users are able to act like superheroes without 'real-world' consequences. Vaajakallio [37] defines the main characteristics of games as play and performance. Play is voluntary, non-serious, intensive, and immersive, and it is conducted based on pure pleasure. It proceeds within its own proper boundaries between time and space according to fixed rules and in an orderly manner. It has its own magical circle in which the play proceeds. Sticking to the rules is enforced—if you break the rules you are inventing a new game or play. Today, children increase their knowledge through playing games, and they learn to collaborate when playing massive multiplayer games simultaneously.

Deterding et al. [38] point out that in game studies, this distinction between games and play is mostly tied back to Caillois's concepts [39] of *paidia* ('playing') and *ludus* ('gaming') as two ends of play activities. The paidia or 'playing' indicates a more freeform, expressive, improvisational, even 'tumultuous' recombination of behaviors and meanings, whereas ludus (or 'gaming') captures playing structured by rules and competitive striving toward goals [36].

According to Deterding et al. [38] there are tendencies to describe gamification both practically and in terms of client benefits. Helgason [40] sees gamification as 'the adoption of game technology and game design methods outside of the games industry'. Zicherman [41] sees it as 'the process of using game thinking and game mechanics to solve problems and engage users', or 'integrating game dynamics into your site, service, community, content or campaign, in order to drive participation'.

Salen and Zimmerman [42] studied games through a series of 18 'game design schemas', or conceptual frameworks, including games as the systems of emergence and information, as contexts for social play, as a storytelling medium, and as the sites of cultural resistance. Deterding et al. define gamification as the 'use of game design elements in non-game contexts' [38, p. 1]. They point out that gamification relates to games, not play (or playfulness), where 'play' can be conceived of as the broader, looser category, containing but different from 'games' [42]. Gamification is commonly implemented by taking the scoring elements of video games, such as points, levels, and achievements, and applying them to a different context. The concept has been used in loyalty systems such as frequent flyer miles, green stamps, and library summer reading programmes. According to Zichermann and Cunningham, these gamification programmes can increase the use of a service and change behavior, as users work toward meeting set goals to reach external rewards [43, p. 32].

Nicholson [44] exposes two major concerns related to gamification. The first is related to the name, 'game', which implies that the entire activity will become an engaging experience, whereas in reality gamification uses only the scoring system and is more closely akin to 'pointsification' [45]. The core message of these criticisms of gamification is that there are more effective ways than a scoring system to engage users. The second concern is that the organisations getting involved in gamification are not aware of the potential long-term negative impact of gamification. Underlying the concept of gamification is motivation. People can be driven to do something because of internal or external motivations [44]. Suppose an organisation that has been using gamification based upon external rewards decides to stop the rewards programme; the resulting situation will be worse than the pre-gamification scenario. This happens because users are less likely to return to the behavior without the external reward [46]. These beliefs regarding internal motivation and extrinsic rewards are unproven. The authors of the book *Gamification by Design* do admit, though, that 'once you start giving someone a reward, you have to keep her in that reward loop forever' [43, p. 32].

As noted, people are driven to do something by internal and external motivations. Often, the information on a consumer's energy consumption is based on current status, but hardly ever does the consumer think about the reasons behind the increased consumption. Rather than using a point system, meaningful gamification encourages a deeper integration of game mechanisms into non-game contexts. A good example of meaningful gamification would be its use as applied to energy consumption behavior.

Social rewards can be used to motivate people to save energy. There are solutions currently available that enable people to upload their consumption data to the Internet. Good energy-saving results may gain appreciation from others. The data can be anonymous or not. An energy monitoring solution-provides a feed-forward method to show what consequences particular behaviors will have [15]. For example, consumers can be informed of how long it takes to consume 10,000 kWh with their current energy-use behavior.

3 Case Kalasatama—Helsinki

In this section we present the Kalasatama field site, the main actors, and the views of the Kalasatama residents. Our case study is focused on the residents' views. We conducted in-depth empirical user research in order to understand the conventional energy-consuming behaviors of Kalasatama residents and their social interactions within the community.

3.1 The Field Site

Kalasatama (Figure 7) is one of the areas in which the city of Helsinki is conducting an experiment using a 'smart urban innovation' concept. The label of the development project is 'Fiksu (= smart) Kalasatama'. With the project, Helsinki is aiming to start smart city development. The concept of smart cities implies an integrated framework of being instrumented, interconnected, and intelligent [47]. Kalasatama is one of the five smart districts being developed in Helsinki but is the only test bed for 'smart urban innovation' among the five. Therefore, there are many ongoing programmes that experiment with intertwining smart technology, innovation service systems, and resource efficiency with people and the community. The construction period of Kalasatama is from 2009 until the 2030s. By 2030, Kalasatama is forecast to provide 5,000 to 7,000 housing units to accommodate 20,000 residents. In addition, there will be 8,000 job placements in the area by 2030. The motto of Kalasatama is 'One More Hour a Day', which means to save one hour a day for the residents. This will be achieved through 'efficiency' in daily life, for example, smart services, resource efficiency, co-creation, and agile piloting. The programmes running currently in Kalasatama are the waste management system, e-car renting, bike parking, and communal laundry and sauna services.

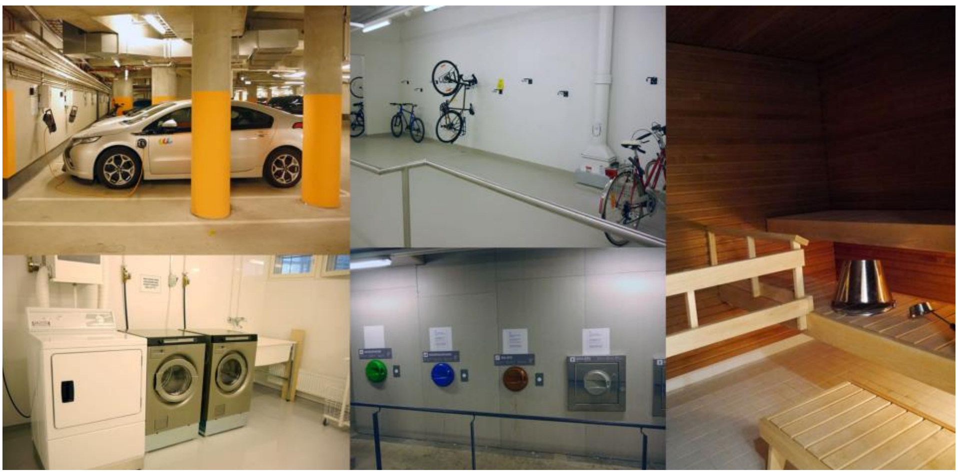

Figure 7: ***Photographs from Kalasatama***

3.2 Key Actors

In this section we present the roles and views of the key actors. The main emphasis is put on the views of the residents; the user study is presented in its own chapter. In addition to the actual residents, Helsingin Energia plays a crucial role. The city of Helsinki is represented by Forum Virium, which is the appointed city developer of Kalasatama.

The Helsingin Energia company provides the energy for the residents of the area. It is one of the biggest energy companies in Finland, selling electricity to about 400,000 customers and district heat to over 90% of properties in Helsinki. In Kalasatama, the company is building a smart energy system. Currently, the system can be used to monitor a home's electricity devices via the Internet from outside of the home, with, for example, a mobile phone. For instance, a person could turn the sauna on before coming home or check whether the coffee maker was switched off after leaving home. The actual direct energy savings in economic terms are not very significant for an average person living in an apartment building, but other advantages can be considerable—for example, a water leakage can be noticed more easily.

A representative of Helsingin Energia stated that the most interesting aspect of this system is that it makes it possible to create new applications and ways to use it in the future. Thus, the issue we are dealing with in our article—the optimisation of energy prices to balance consumption peaks—could be tackled through these kinds of systems. According to Helsingin Energia, the system is easier to include in new buildings but could be added to old buildings while conducting plumbing and electricity repairs.

Forum Virium was founded in 2005 and is owned by the city of Helsinki. It consists of 20 member organisations from public and private sectors, but also works in collaboration with a variety of small- and medium-sized enterprises for the smart city development goal. Forum Virium's interest in Kalasatama is to 'see how smart city elements could be distributed over Helsinki' (interview of Veera Mustonen). The aim of Forum Virium is also to target the public and to engage them with efficiency and community activities.

One aspect of the project is the open data platform that Forum Virium has been developing. The aim of the platform is to help society increase the equality and involvement of all sectors. It can mobilise great creative reserves and user-oriented design [48]. However, in the interview, Veera noted, '… there is a lot of data about energy consumption collected or going to be collected; however, this is still in its progress of exploring how we could utilize the data'. As noted, there is an efficiency goal of 'one more hour a day' in the plans for the Kalasatama region, but there is not yet a service system that could help to achieve this goal through the use of efficiency data. Additionally, there are not yet any plans on how the data could be extended for community-level use.

3.3 User Research

We started from *micro level*, as suggested by Shove [10], conducting an empirical study of individuals and families in order to find out what their needs and expectations are, and revealing their rationales and motivations toward the goal. Having understood the individual reasoning, we moved to the *meso level,* where we could see the collective practice and social order. To provide new insights, we looked also at how new practices could be acquired. The findings of the user research also have implications regarding the *macro level*, as they show how technology and user practices can interact and be integrated for sustainable new habits of consuming energy.

Our analysis was based on the identification of three main notable elements within the system: the flexibility of time (*flexitime*), social order, and technology. The framework for the two latter aspects is provided in the policy and ICT sections. This section thus concentrates on the question of what *flexitime* means to the energy consumers in Kalasatama: What are their rationales for being flexible in consuming electricity at home? What do they expect regarding rescheduling their electricity-related housework? What are their collective conventions in consuming electricity at home?

3.3.1 Reasoning behind Energy-Consuming Practices—From What People Say and Do

The peak time of the collective convention in consuming energy at home in Kalasatama is in the evening after work. The peak hours are from 5 to 9 PM. The main household electricity-consuming activities we identified in Kalasatama are cooking, laundering, showering, vacuuming, ironing, heating, working on computers, listening to music, and so on. To achieve *flexitime*, we asked the residents if they could move their activities to the non-peak hours. Obviously, some of the activities are less likely to be moved, for example, cooking, working on computers, and listening to music.

Some of the people interviewed had a strong sense of self-autonomy and individuality regarding the whole idea of proposed flexibility. For example, one interviewee stated: 'Helsingin Energia can't change my life in any way. I will do whatever I want'. There was also some doubt about whether flexitime could be achieved on collective grounds. As one interviewee stated: 'To me collective praise never really functions. Since people can't control other people's doings…'.

It also came clear that when it comes to reasons behind different energy consumption patterns, both intrinsic (from personal beliefs and values, for example, from concern for nature and responsibility for future) and extrinsic (for example, through monetary rewards) values existed. Sometimes these both were acknowledged, as stated in the following interviewee comment:

> *I am trying to time my electricity usage so that it would be ecological. But I'm not doing it for any praise but simply because I feel it's my responsibility to the coming generations. Praise or not, I act the way I act. But money, that stuff does talk!*

However, the monetary rewards were not considered as significant as one might think. One interviewee stated that he does not even read the electricity bill. Thus, saving energy was not anchored on money concerns but instead on ecological concerns. However, some amount of compensation was expected when they were asked about changing their routines. Our study also found that some people are not really calculating the amount of compensation; instead, a symbolic compensation of 5% is enough to motivate them to act.

The cultural conventions impeding energy savings or flexibility were acknowledged by the interviewees. Whereas some habits are easily changed, others might need huge adjustments and would not be considered the first on the list if needing to move toward more flexibility. As one interviewee noted: 'Finns care about energy saving, but we do like sauna'.

In addition, when it works somewhere, residents seem to believe it will work in Kalasatama too. This reinforces the possible realisation of their expectations. 'The *electricity bill reduction* that has been in use in some areas seems like a very efficient idea to me,', stated one interviewee.

Residents also value the sense of community. The interviewees, for example, valued the intimate neighbourhood relationships and especially the fact that people in Kalasatama are used to saying 'hi' to each other.

Finally, we found that there is mistrust between the energy users and the energy provider. As one interviewee stated: 'I don't know [if] we are consuming hydropower, even if, I don't trust! Haha!' This is affecting people's expectations regarding energy consumption, and there must be a solution to bridge the gap and work toward a co-evolution strategy.

3.3.2 Residents' Motivations

From the findings just discussed, we noted the following values related to the motivation of the residents for doing housework flexibly and creating new habits: earnest concern for ecology, responsibility to the future, self-autonomy, individuality, expectation for compensation, utilitarian value, the symbolic meaning of compensation, and others such as cultural conventions and community spirit. Last, we found mistrust between the energy users and the energy provider. Overall, we felt a sense of humor, and ironic comments during our conversations with the Kalasatama energy users. This reflects one characteristic of the residents that we believed could further develop our solution—their unique sense of humor.

All of these identified values are critical to take into account in planning if the goal is to change the way the residents act and steer them toward new habits. How, then, could we capitalise on these values and enable new social arrangements for energy consumption?

To answer this question, the following aspects as related to the identified values are important:

- **Ecological concern and responsibility to the future** can be seen as residents' long-term commitment to doing social good. These are the intrinsic values that could be seen as very strong motivators.
- **Compensation, utilitarian value, and the symbolic meaning of compensation** are generic and could be seen as an additional driving force for them to act more promptly and efficiently.

- **Values of self-autonomy and individuality** represent residents' agency in re-scheduling their house activities. We could see that if they are given the tools enabling them to act and construct their schedules on their own, it will be a significant drive. They could be empowered to be knowledgeable and capable agents driving toward energy efficiency. The given tools could help them to respond flexibly, plan ahead, and establish rhythms for their own lives yet with the provided technology and within the flexitime structure/framework.
- **Community value** seems to be a value that conflicts with self-autonomy and individuality. However, if the individual mode works well, this will have a role model and ripple effect, reproducing the *flexitime* value through social interactions among the neighbourhood cumulatively. This social effect could be augmented especially when the sense of community has been grounded in Kalasatama. The shift from individual act to collective practice has long-term cumulative consequences for the (new) social order [10, p. 181]. Particularly, we see a community spirit in the public areas in Kalasatama, and residents are keen on conversing in the public space on Facebook.
- **Cultural convention** is a cultural value that we would consider further if the cultural framework is relevant in achieving our objective.
- **Humor** is an important criterion that we will put into our framework.

3.3.3 Opportunities for Change

With the values identified and described, we next sought opportunities for us to design the tools for the energy users in Kalasatama. We identified several elements that are crucial when planning the tools.

Users as the decision makers:

- A system that enables users *to schedule* valued time/activities, to realise self-autonomy within the technology structure
- A system that provides instant information so users can *react fast and act* immediately
- A system that provides a trend/forecast so users can *plan ahead*
- A system in which compensation is necessary but has only *symbolic* significance

Users as the active influencers:

- In the long run, the system should have a function that would allow users to compare and discuss flexitime activities among their peer neighbours in order to form a 'flexitime culture'. When a pattern of everyday behavior is constructed in a community, it tends to become a foreseeable path leading toward sustainable new habits.
- To respond to the self-autonomy value, the system should provide an 'exit clause' mode for the *users to choose to stop* the programme at their own will.

Users as the creative participants:

- A solution embedding playfulness would echo the sense of humor characteristic of Kalasatama residents. Yet the notion of 'play' here should be interpreted as a 'serious' play providing a 'playful' and encouraging experience, rather than the play value of a toy for children.
- Last, the system should provide feedback for the users; it could be feedback (reinforcement to reinforce the propelling progress) on the energy saved in monetary terms or kWh. This concept is borrowed from Shove's discussion of the self-propelling spiral effect [10].

After outlining the opportunities, we did another round of user research to discover how residents would like their system to be. First of all, the users stated that they need to have their own as well as the area's monthly energy consumption and comparisons with the previous 6 months' energy consumption. The information could be retrieved either from a mobile phone or with a plugin in a toolbar.

Other desired features included goal-setting capabilities, warnings/alarms, rewards, reminders, and feedback. A graphical design would be preferred, with colours and text included. The interface should not be patronising and it should allow the management of energy consumption to be done easily.

The full list of questions can be found in Appendix B.

4 *Our Proposals for Action*

In our gamification solution, we present a simple idea for a community-based online game that will motivate users to be smart electricity users. The goal of such a game is to encourage the flexible use of electricity. Because most of the users currently own a smart phone, the game could be a smart phone–based game application, or it could also be a game app that is plugged into a social media platform such as Facebook.

People who live in a community such as Kalasatama would use this game to get connected with the other players from their community; they could also choose to join other communities where their friends or family live. The basic functionality of the game would consist of giving each individual points based on his or her smart and flexible use of electricity.

First, we assume that people will get feedback about their consumption data for each day, and their previous consumption data daily for the current week, weekly for the current month, and monthly from the time the user starts using the game. In addition, the energy providers would publish the forecast of the hourly electricity price for the day in advance on the company's server or make the price data directly available to the application server. Once users have the price data available, they could then schedule their daily routines for the following day based on the price and available renewable energy.

The game service provider would be able to fetch the consumption data of any user and then decide, based on the data, whether the user has made smart decisions about daily electricity consumption. If a user has made a smart decision—for example, consuming the largest percentage of daily consumption of electricity during the cheapest hours—then the user would be awarded points. Users would be able to check their own positions within the community group through ranking. In such a way, the game would encourage positive competition within the community. On the other hand, if users are not willing to compete with others but themselves only, they could choose that option and compare their consumption data with those of previous months, for example.

Each month, the game could award the top three users of the community as the 'smartest electricity users'. Once the smartest users have been identified, there should be some kind of a reward or incentive for them from the energy provider. Based on the interviews we performed, the users seem interested in receiving a small monetary incentive for being smart; however incentives such as awarding movie tickets or free vegetables from 'Urban Farming', the Food Co-ops, would make the game more interesting for the players.

Our basic idea is to engage the users in making smart decisions about their daily activities regarding their electricity consumption and to make the energy provider benefit from the flexible usage patterns of its users. In the long run, this will allow a flexible demand-based electricity production system and more viable use of greener energy in an energy-sustainable society.

Finland is developing a model area for a smart power grid in the new Kalasatama district. The aim is to help to lower consumption and emissions with the implementation of state-of-the-art energy, information, and automation technology. Users are able to follow their own energy consumption patterns and consume less energy. To make it more enjoyable, they can invite their neighbours to share their figures via a community called SmartHousebook. If a user manages to save more than the average one-block consumption, the extra is stored or, even better, the user's house is dazzling with illumination in dark seasons, which invites people to gather outside and makes the surroundings lively. Surroundings can also be enhanced by using the Percent for Public Art Program, which recommends that a minimum of 1% of the gross construction cost of each significant development be contributed to public art. One endeavor aims to locate art in places where it has not previously been.

5 Conclusions

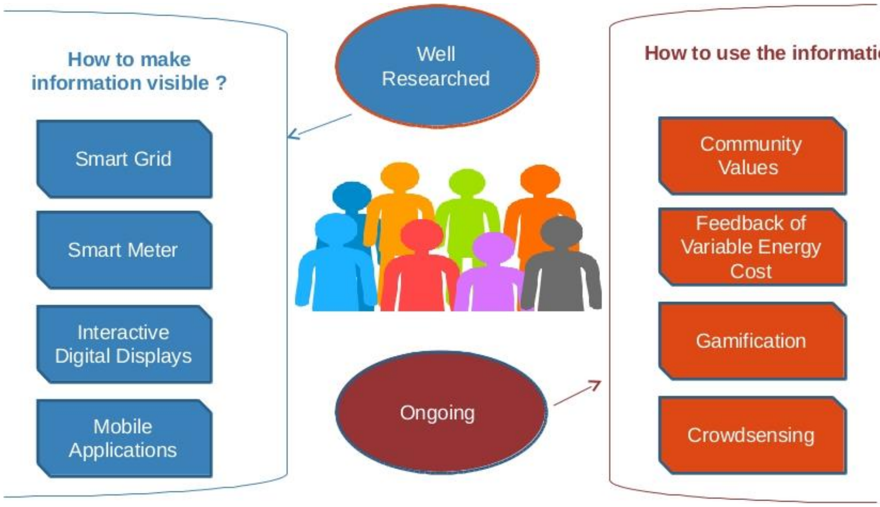

Fig. 8. ***Role of ICT—current scenario and possible future research directions***

Figure 8 depicts presents the role of ICT in reducing the energy consumption of end users. So far, the research has extensively focused on finding out how to make energy consumption data available to users and how efficiently they can visualise it. As a result, we now have a lot of data about electricity usage patterns in hand. However, we know very little about how to effectively utilise these data to help the end users to reduce their energy consumption. Forum Virium raised the same concern during our interview. More specifically, the concern came out as: 'There is a lot of data about energy consumption collected or going to be collected; however, this is still in its progress of exploring how we could utilise the data', or 'currently the data is used only for individual level, not yet extended to community level'. Also, with only the huge amounts of data without further processing and implementation, 'there is not yet a service system to realise the "efficiency" goal'.

So as Figure 8 suggests, the majority of the research on this aspect so far has focused on smart cities with smart electricity grids and smart meters in homes to collect data about energy consumption, and with mobile application displays and interactive digital displays to communicate the consumption data to end users. The problem now is to effectively utilise the data to achieve a reduction in energy consumption. Four possible ways of utilising the data toward achieving the goal of reduced energy consumption are shown in Figure 8.

In this aspect, ICT can play a major role by providing new services, applications, and communication scenarios. We have performed an extensive survey on how community values can be utilised in this scenario—specifically, we identified the triggering factors of the behavioral changes of the users to achieve the goal. Energy providers could have an important role in making the ICT solutions part of their service package for consumers. In the end, though, we would also need policies that would support both the usage of renewable energy sources (for example, with feed-in premiums; see section 2.1) as well as flexible energy use. To achieve the latter target, the elements presented in section 3.2.3 could be used as a starting point to construct effective policies.

As mentioned earlier, we are looking toward an energy-sustainable society of the future where the electricity production is expected to be dominated by sustainable sources such as solar or wind. In such scenarios, it is of utmost importance to make the energy demand flexible because the production source will not be available at a constant rate throughout 24-hour period. With the use of ICT (web applications, mobile applications, etc.), a day-ahead forecast of the production or the real-time energy availability data can be made visible to users more effectively so that they can predict and change their energy consumption behavior accordingly. Gamification and crowdsensing are also two important tools that can effectively engage consumers, communities, and energy-producing firms in reducing energy usage. ICT can be the underlying enabler of these tools for making the data visible to different parties.

We also predict that there will be an introduction of a third-party service provider in this scenario that will make use of the consumption data available to provide services that will eventually reduce the energy consumption and trigger changes in user behaviors and consumption patterns. As mentioned earlier, ICT will play a major role and act as an enabler for an energy-sustainable society in future.

We started from the emergent global issue of climate change, seeing the urgent need of promoting renewable energy and flexibility in energy consumption. After our literature review, we understood that flexibility would need to be transferred from the energy production side to the energy use side, which is to be flexible in energy demand. In order to cope with this, we could see that a change in conventional energy consumption behavior is unavoidable. However, to change an established behavior is not easy, as it has been socially constructed and strong social beliefs and values are embedded tightly in the system. At the same time, we could see how technology has been integrated in our lifestyle, and Finland is in the leading position among the world in the technology sector. We identified that the ever-faster developing ICT could be utilised in the new social arrangement of forming new energy consumption habits.

Then we came up with the concept of 'flexibility via ICT' in energy consumption.

In the next phase, we conducted empirical studies looking into the existing energy consumption behavior. Only by this method could we identify the motivations of the energy users in anticipating new sustainable habits. We did our field work in Kalasatama, the test-bed smart district in Helsinki. Taking our approach from the social perspective, we understood how individual rationale interacts with societal factors in the social process of energy consumption. Simultaneously, we had a discussion with a representative of Helsingin Energia, the energy provider in Helsinki. This is because Helsingin Energia's strategies and policy making provide a framework in which users act and hence shape their long-term behavior. From our user research, we identified several key values of the energy users in Kalasatama, including the values of self-autonomy, community, responsibility to the future, and, last but not least, a sense of humor!

The insights from the empirical studies led us to the opportunity of 'flexitime via gamification'. We have explained several possible designs for utilising gamification as an enabling system to empower energy users in rescheduling their home activities on their own. This would realise their values regarding self-autonomy and ecological concern and, ultimately, enable them to be knowledgeable and capable agents driving toward energy efficiency.

Driven by intrinsic values and aided by the use of the enabling system, integrated with corresponding energy policies and regulations, energy users can act in the socio-technical landscape on a self-propelling path toward energy efficiency. By 2035, we foresee that a 'flexitime' culture of energy consumption would be formed. New energy habits will be reflected not only within the private realm of performing household activities, but also in daily activities within the community. Extending from the Kalasatama district, the city of Helsinki is becoming an energy-efficient city.

Acknowledgments

We would like to thank Atte Kallio from Helsingin Energia and Veera Mustonen from Forum Virium for giving us the time to interview them and offering their thoughts and comments on this paper. We also thank the residents of Kalasatama who participated in our user research and thus enabled our work.

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Appendix A

Kalasatama User Research

Fieldwork carried out October–November, 2014

<u>Semi-structured questions:</u>

1. According to some studies, the peak hours of household activities using energy are 5–9 PM; is it your lifestyle, too? If not, can you tell me your peak hours?
   Note: Household activities like cooking, watching TV, dishwashing, laundry, ironing, bathing, vacuuming, working on computers, reading with light on, heating, etc.

2. Specifically, what are you doing between 5–9 PM (including both [a] household activities and/or [b] home-working activities)?

3. Do you think you can flexibly move your activities to before 5 PM or after 9 PM? And which activities can you move?

4. If you cannot move activities, can you tell me why?

5. How about if Helsingin Energia is now suggesting a compensation to you if you change your peak hours?

6. What kind of compensation do you prefer—for example, electricity bill reduction? If so, is a 20% reduction OK? How about a certificate or commendation to you?

7. What do you think about the community spirit in Kalasatama?

8. If the neighbourhood atmosphere is good, how about a community/collective commendation? For example, if Block A in Kalasatama saves a certain amount of energy in one month, then Kalasatama will display this in the public area in the district? Do you think this collective goal will be more encouraging than individual achievement?

9. Other ideas?

Appendix B

Kalasatama User Research

Fieldwork carried out October–November, 2014

'To me collective praise never really functions. Since people can't control other people's doings… they are not motived at all to react to the incentive. I don't think I would really care of some house-wise incentive. But then again, I've grown quite some individualist'.

'I am trying to time my electricity usage so that it would be ecological, but I'm not doing it for any praise but simply because I feel it's my responsibility to the coming generations. Praise or not, I act the way I act. But money, that stuff does talk! '

'Yes! We all concern about saving energy!'

'it's just little money, I don't read the electricity bill much'

'Finns are concerned about energy saving, but we like sauna'.

'… people don't really look that much into 'how large' the compensation actually is…. People are happy with the idea of compensation and 5% should already motivate people. From 5% onwards, it won't make much difference in the motivation effect'.

'with compensation, yes I could possibly move my household activities to other time'.

'the electricity bill reduction that has been in use in some areas seems like a very efficient idea to me'.

'I am living life of a modern middle age women, I take care of myself in everyday life. I clean my flat when I have an inspiration and we have here the free laundry. I don't watch TV (why on earth?) but I am really some person and also catch my music enjoyment from Youtube. Helsingin Energia can't change my life in any way, I will do whatever I want'.

'yes, the quality of the food is good and more importantly it is good to support our community'.

'here the neighbourhood relationship is intimate, neighbours say hi to each other'.

'I didn't know we are consuming hydropower, even if, I don't trust! Haha!'

Appendix C

Second Kalasatama User Research for User Preferences

Fieldwork carried out November, 2014

What information you would like to receive?

1. my own 'monthly' energy consumption
2. a historical trend of my energy consumption, for the past 6 months
3. I want to see the total energy consumption of Kalasatama
4. I would like to have a comparison to other districts with similar characteristics (population, house types...)
5. other information I would like to know: water and heating consumption

How you would like to receive the information?

1. via mobile phone (just push a button to see) or a web browser
2. plugin to show it in the toolbar (funky!)

Other features:

1. 'Goal-setting', e.g., I can set my 'energy price goal' and then receive an alert when the price reaches my preset goal.
2. Also 'a guarantee of the price for the next few hours'; otherwise, it does not help much to get cheap electricity for 10 mins if the cooking or washing takes 3 hrs.
3. 'Maximum energy consumption' set by myself, and hence with
4. 'Warning alarm' if I have consumed excess energy that day.
5. 'Reward' if I consume wisely (consume less and at a low price), e.g., reward in terms of a price discount on energy or an hour of free energy usage; actually, the format of reward does not matter because I am a conscious energy user, just something simple and symbolic is good enough.
6. 'Gentle reminder' or 'suggestion' from energy company to give some advice on energy consumption: some say yes, but some say that it is even worse (i.e., no need to give advice).
7. 'Feedback' mode to show when they 'like' or 'dislike' some features

The information display format:

1. Graph is preferred.
2. Graph with color (e.g., green means you are using less energy, yellow means you are consuming more, red means you are consuming too much; similar to the Travel Card Reader) is preferred.
3. Graph supported with text (graph on top to show main information and text underneath for those interested in deeper information/analysis) is preferred.

What kind of interface will motivate them more?

1. A friendly and welcoming one, not patronising
2. Smart so as to manage the consumption easily

Future of Energy: Powered by Solar

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Abstract. Solar energy, radiant light and heat from the sun, is ubiquitous. It exists everywhere and is available for any one of us to use. Global, sustainable growth could be supported and environmental impacts, caused by the production of electricity, limited by an increased use of solar energy. The daily and yearly solar irradiation is especially high close to the equator and in areas of our globe affected by desertification. However, countries excelling in the areas of investments made in and the use of solar power are high-technology countries located at less optimal latitudes. This paper presents a state-of-art study and discussion of the opportunities and barriers to accelerate the use of solar power. Three interlinked visions are discussed: (1) the 100% scenario assuming that the total global electricity demand could be covered with solar energy only, (2) the global-electricity-grid scenario suggesting a global electricity market supplied by large-scale photovoltaic plants, and (3) the energy-for-all scenario presenting wide-scale adoption of solar technologies as a means to tackle climate injustice and change by entering current nonconsumer markets.

Keywords: solar energy, photovoltaics, electricity, climate change, future

1 Introduction

Solar energy is ubiquitous. It exists everywhere on the globe. Germany made the headlines in early June 2014 by being able, for the first time, to cover more than 50% of the country's electricity demand with energy collected via photovoltaic panels [1]. From a global perspective, the equivalent percentages are very low. Why is the market share for solar energy not bigger? What are the current barriers and opportunities? How would a substantial increase in the use of solar power impact our future?

Solar energy can be defined as radiant light and heat from the sun. The concept of the use of solar power in this paper refers to the direct collection, use, and distribution of solar energy by implementing active solar technologies, such as photovoltaic (PV) panels, for electricity production. This paper presents a state-of-the-art study and discussion of the feasibility of accelerating the use of solar power. The discussion is based on a literature review, interviews, and data collection.

2 State of the Art

2.1 Solar-Powered Technologies for Electricity Production

The generation of electricity from solar power is based on the photovoltaic effect: the capacity of materials (semiconductors) to generate electricity when exposed to solar radiation. When exposed to sunlight, electrons are emitted from the materials, and the electrons remaining in the materials create positive and negative bands that can be employed by electrical circuits. Until 2014, crystalline silicon (Si) was the most prevalent material for the production of PV cells, accounting for 62% of all modules produced (Figure 1 [2]). Currently, thin-film technology and other emerging technologies are gradually taking up more market share.

With the progress of PV technology, the production of solar cells is increasing yearly, with Asian Pacific areas as the leaders. The majority of PV cell installations are still located in European countries (see Figure 2) [3]. However, it is predicted that by 2020 installations in the regions of Asia Pacific and Europe will reach equal levels.

2.1.1 Materials and Manufacturing

Silicon is the leading material in producing solar cells due to its high efficiency and abundance in earth's crust. Monocrystalline silicon panels are manufactured from single-crystal silicon cells connected with each other. Polycrystalline silicon panels are made up of multiple-crystal cells that largely decrease the efficiency of absorbing solar radiation. The cheap price and easy installation of polycrystalline panels may contribute to their growing market share; however, they are not as efficient panels made of monocrystalline silicon. Figure 3 [4] shows a comparison of the structures of both types of cells.

Two technological strategies have been suggested to increase the module efficiency of crystalline silicon solar cells: (a) decreasing the impurity level of silicon feedstock to reduce the energy payback time and eco-toxicity associated with silicon production [5] and (b) eliminating the use of wafer sawing to help avoid the 50% loss of silicon as sawdust [6].

Numerous alternatives for producing solar cells are being investigated, with a focus on thin-film material (Figure 4 [7]), organic/polymer material, dye-sensitised material, and carbon nanotubes. These are listed and compared in Table 1. To some extent, thin-film material can be considered as a substitution for silicon because of three technological benefits: (1) it employs solar radiation efficiently; (2) it possesses lower temperature coefficients—that is, its power output does not drop quickly when it accumulates lots of heat; and (3), thin-film modules may be manufactured in a continuous production process [8].

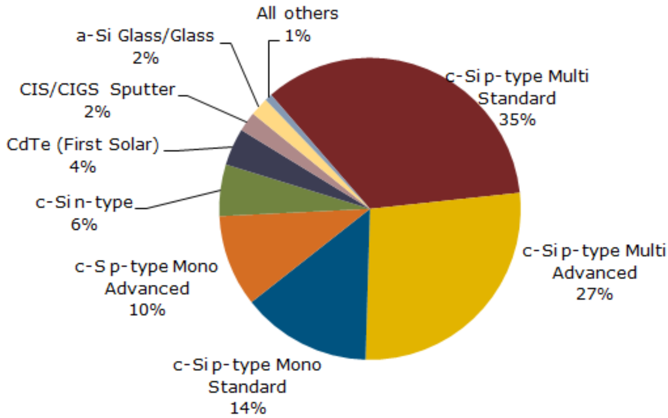

Fig. 1. ***Solar PV module production by technology, 2014 [2]***

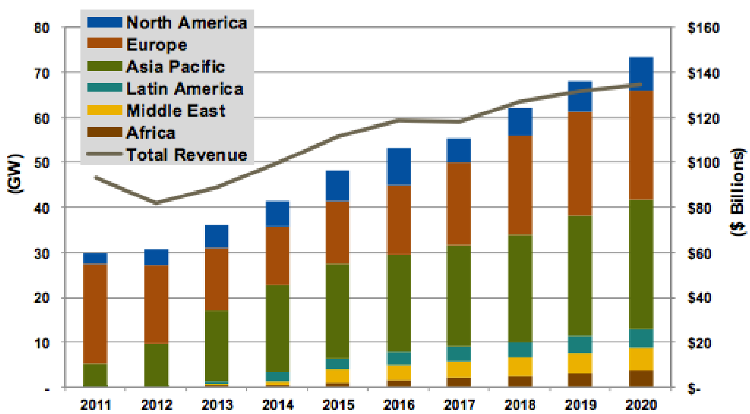

Fig. 2. ***Annual solar PV installation by region, 2011–2020 [3]***

Cadmium telluride (CdTe)-based panels employ a superstrate configuration: Production begins with a glass substrate followed by the deposition of the transparent conducting oxide (TCO, SnO_2: F), the n-type window layer (CdS), the p-type CdTe absorber, and finally the back contact (ZnTe/Cu/C). In terms of large-scale CdTe manufacturing, the issues of cadmium toxicity and telluride availability must be solved. Silicon layers are deposited by plasma-enhanced chemical vapor deposition using mixtures of H_2 and SiH_4 to form amorphous silicon. Despite the advantages of low temperature and low weight during manufacturing, the low cell efficiency and lack of advancements in research largely confine the development of CdTe-based cells [6].

Research on copper indium gallium selenide/copper indium selenide (CIGS) has continued to steadily advance, and this material crossed the 20% efficiency threshold, making it the clear efficiency leader among thin-film technologies [9]. A long-term concern is the availability and price of indium. The recycling of indium will alleviate constraints on CIGS production, but research is needed to develop technologies for efficient and low-cost recycling of all the elements from CIGS modules [6].

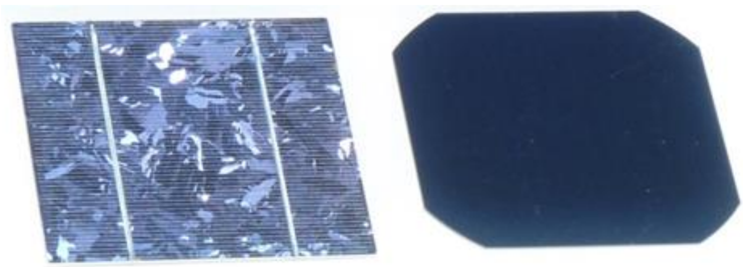

Fig. 3. ***Comparison of solar cells: poly-Si [4]***

Fig. 4. Sample of thin-film solar cell [7]

Concurrently, great attention has been paid to organic/polymer material, dye-sensitised material, and carbon nanotube material. It is easy to prepare dye-sensitised solar cells at a low cost. These cells are semi-transparent, flexible, and durable. What attracts attention is that they perform better than other PV technologies in conditions of low sun radiation and indirect light. Future development should be focused on increasing the efficiency of these cells so that they are competitive with other PV technologies in the commercial market. Sharing similar characteristics with dye-sensitised solar cells, organic and polymer solar cells are easily fabricated into flexible shapes and work in low-sunlight conditions. They can be produced at very low cost in comparison to other PV technologies because they can take advantage of roll-to-roll production techniques in which the organic photovoltaic system is 'printed' onto a continuous sheet of substrate material [10]. Their application in charging electronic devices, for example, backups, laptop cases, tents, and jackets, is promising. Finally, multi-junction cells are able to achieve high conversion efficiency due to their capability to capture electrons within multiple wavelengths of light, yet they are limited to unique applications in aerospace due to the complex fabrication process and high expense [7].

Table 1. ***List of materials utilised in the production of solar cells.***

Materials		**Advantages**	**Challenges**
Crystalline	Monocrystalline Polycrystalline	High quality, low defect, high efficiency	High consumption of active material (Si)
Thin film	Cadmium telluride (CdTe) Amorphous silicon Copper indium gallium selenide/copper indium selenide	High material utilisation, lower cost	Scarcity or toxicity of some materials
Organic and polymer	Polymers and large molecules with repeating structural units	Non-toxic, abundant, low cost, short payback, transparent	Optimisation of lifetime-efficiency-cost tradeoff
Dye sensitised		Environmentally friendly	Low efficiency
Carbon nanotubes			
Multi-junction	One, two, three or more junctions; gallium arsenide (GaAs)	High efficiency	Complex fabrication process, narrow application range

2.1.2 Concentrated PV and Thermal (PVT) Integrated System

Known by a variety of names, such as concentrated photovoltaic thermal (CPVT), combined heat and power solar (CHAPS), or most simply combined heat and power (CHP), these integrated systems capture the wasted heat energy from the photovoltaic system and store it in a heat transfer fluid, such as water, for direct use. CHP systems

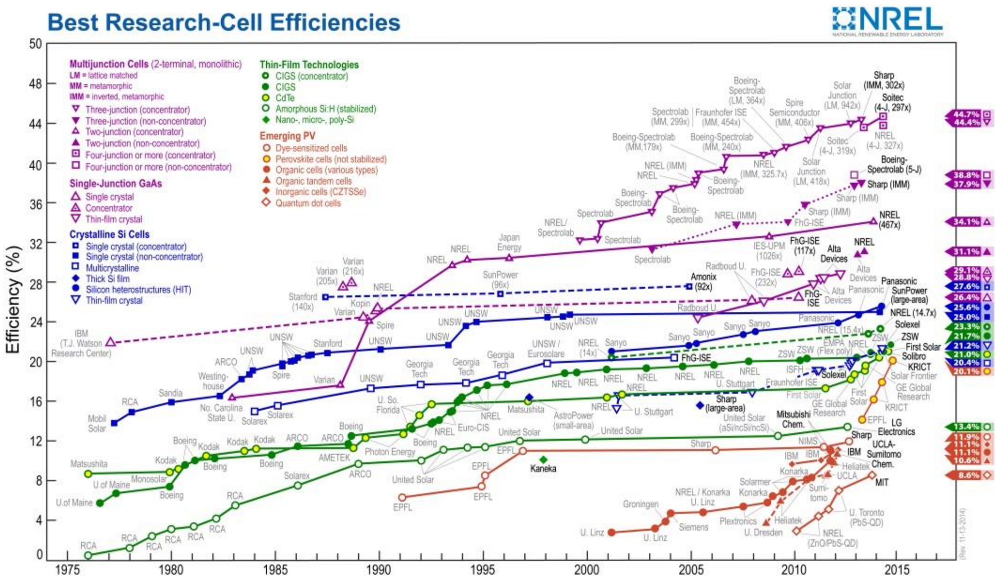

Fig. 5. ***Current PV research efficiencies, as reported by the National Renewable Energy Laboratory [11]***

help to cool the operating temperature of the PV cell, which increases its efficiency in conversion to electrical power while also providing hot water for domestic consumption at temperatures of approximately 80°C. [10].

2.1.3 Efficiency

The efficiency of solar cells is one of the key factors in determining the establishment of technologies in commercial markets. Extensive research is concentrated on efficiency improvement, which is predicted to reach 44% through year 2015 by employing multi-junction technology (Figure 5) [11]. However, large differences in efficiency can be found between lab results and commercial applications, mainly for three reasons. First, the surface areas of cells to be considered vary greatly in terms of the efficiency of a single cell and a module; second, the wires suffer from a great loss of energy when it comes to the transfer of electricity among different modules; and, last, the efficiency in commercialisation lies in the average scale during sorting of solar cells in production, whereas the best results are reported in laboratory circumstances.

The future aim of photovoltaic technologies is to achieve cells with a cost per Watt lower than 1 USD and a commercial efficiency higher than 10%. Currently, only solar cells made of crystalline silicon settle in this target zone. The future development of PV technology is about the tradeoff between cost and efficiency. Products with a high commercial efficiency offered at a low cost are bound to take up larger market shares.

2.2 Sustainability of Photovoltaic Panels

In this section, we look at the sustainability of solar PV panels from two viewpoints: economic and environmental. We analyse these attributes by looking at the life-cycle stages of solar PV panels. Because this type of analysis depends on contesting parameters, we present a simplistic analysis assuming an average irradiation of 1,500 kWh/m^2/yr and crystalline silicon and thin-film PV panels with approximately 10% efficiency.

2.2.1 Economics

Three major factors contribute to the economics of solar power technologies:

1. initial investment cost and return on investment,
2. maintenance costs, and
3. land use.

The current low penetration of utility-scale solar power is primarily attributed to the high investment costs. The estimated average investment for a simple home-based solar panel for an average-sized home is around 20,000 USD. The payback time is typically around 15 to 20 years. In terms of cost per kWh, conservative estimates place current solar power at 28 to 42 cents/kWh, which is many times higher than the 5 cents/kWh cost for power from a typical natural gas plant. The high investment costs can be attributed to the high manufacturing costs. It is estimated that mass production of PV panels will bring down the cost. New technologies have played an important role in this progress: The expenditure required to produce thin-film solar cells is lower by a factor of two than that for multi-crystalline silicon-based modules, currently the dominant technology in the market.

Some companies have made use of this barrier of high initial investment and tried to reduce the burden on end customers by creating innovative leasing plans. Examples of such companies include the Solarcity [12] and construction companies like Lennar Homes [13]. Governmental subsidies exemplify another approach playing an important role in making these numbers feasible. Even though utility-scale solar installations are not yet cost effective, commercial-scale installations have almost attained cost parity with fossil fuel–based electricity generation [14].

The costs of maintenance are usually not considered when talking about solar panels. It is a known fact that solar panels have a reduced output if not cleaned regularly. The main categories of related costs generally referred to as 'business costs' are (1) maintenance and cleaning costs, (2) installation labour costs, and (3) other hardware costs, such as wiring, batteries, and other components. These items constitute about 20–30% of a typical PV system's price [15].

Many studies prove that the availability of land is not an issue. There is no limit to where solar can be placed, and solar panels consume much less land than a typical coal plant [16].

2.2.2 Environmental Impact

It has been established by research that solar electricity production is much more environmentally friendly than that based on fossil fuels. In this section, we analyse the two major solar panel types currently dominating the market and their environmental impacts.

Silicon-based PV panels release pollutants such as sulfur dioxide (SO_2) and nitrogen oxide (NO_X). During the life cycle of silicon-based panels these comprise, like their greenhouse gas (GHG) emissions, only 2–4% of those from fossil-fuel plants. Some facilities producing tandem a-Si/mc-Si use potent greenhouse gases, like sulfur hexafluoride (SF_6) or nitrogen trifluoride (NF_3), as reactor cleaning agents, but they can be replaced or their emissions abated. Replacing grid electricity with silicon-based PV systems would result in 89–98% reductions in the emissions of GHGs, criteria pollutants, heavy metals, and radioactive species [17].

CdTe thin-film panels use cadmium (Cd) and tellurium (Te), both of which are by-products of copper and zinc production. There are currently no technologies or production pipelines to efficiently extract these from copper ore, mostly because it is not profitable enough. Thus the availability and cost of these panels will depend on the usage of copper. These panels are easily recyclable at the end of their life cycle, making their end-of-life cost negligible. Direct Cd emissions from the life cycle of CdTe modules are estimated to be 90 to 300 times lower than those from coal power plants. Indirect Cd emissions include those from using fossil fuels, such as natural gas or coal, for the processing, manufacture, and transportation of these materials throughout the life cycle of the PV modules. The dominant sources of such indirect Cd emissions were found to be the use of coal during steel-making processes and the use of natural gas during glass-making processes. The direct emissions of Cd during the life cycle of CdTe PV are 10 times lower than the indirect emissions due to the electricity and fuel use in the same life cycle, and about 30 times lower than those indirect emissions in the life cycle of crystalline photovoltaics [18].

2.3 Distribution of Electricity

The transmission and storage of electricity are obstacles to increasing the use of solar power. The fact that the earth rotates around the sun and thus, consequently, half of the globe's surface is deprived of solar radiation at any given time, as well as the interrelated distribution and storage issues, challenge the solar power ecosystem.

Two important barriers need to be overcome:

1. Availability: The availability of solar radiation only at certain times of day makes it difficult to generate and supply electricity throughout all 24 hours. Either additional electricity must be generated during daytime and stored for use later (e.g., during dark nights), or electricity needs to be generated and transmitted from one place to another (i.e., where the sun currently shines to the other side of the globe). As

shown in Figure 6 [19], solar radiation is, in any given location, unavailable for a large portion of the day and typically at times when the demand is high.

2. Variability: The impact of intermittent sources (e.g., solar and wind) is highly detrimental to the traditional electricity grid if their contribution becomes significant compared to conventional electricity. Renewables like solar energy pose new problems to the planning and efficient utilisation of the transmission infrastructure.

Variability causes stress on the energy grid. Traditional grids are not designed to support intermittent sources of energy. The traditional grid can handle large power plants, sized 200 MW or more, and regulate vertically integrated utilities [20]. As a result, it cannot cope if the percentage of intermittent generation hits a significant percentage of total supply. Grids need to be upgraded to a so-called smart grid, where both the bidirectional energy flow and related information flow are utilised for the operation and management of the grid [21].

2.3.1 Decentralised or Centralised Electricity Production?

The traditional mode of electricity production and distribution relies on the existence of centralised power plants delivering energy to the end user. This constellation is now changing, with the end-user role developing from being a passive consumer to an active co-provider [22]. Today electricity can be supplied by distributed power plants.

The first peer-to-peer electricity sales between consumers have also been activated [22]. For example, Oulun Sähkömyynti in Finland offers micro-generated electricity produced by local farmers [23].

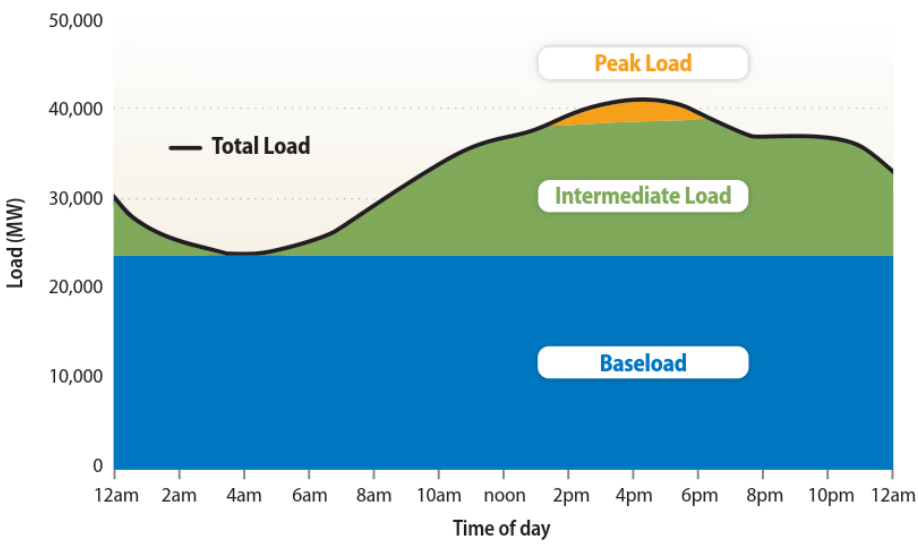

Fig. 6. *Day electricity load curve in California, summer 2009 [19]*

Another approach to decentralisation is to centralise the power production but distribute the ownership. One recent example utilising this approach is the biggest Finnish solar power plant to be built so far: the Suvilahti plant, which has 1,200 solar panels and an estimated annual production volume of about 260 MWh and an output efficiency of 300 kWh. Power production began January 3, 2015. [24] The actual plant was built with centralised funds, but consumers have the opportunity to rent one to five solar panels for a fee of 5.50 USD per month per panel. The rent is reimbursed against the actual electricity production of the plant [25].

Both centralised and distributed systems have advantages and disadvantages. A centralised system gives the potential to produce huge amounts of energy in a suitable location. However, such a centralised system has its risks. For example, around 25% of energy is wasted in traditional systems due to transmission losses. Other challenges include reliability-related issues such as political instability and bureaucracy when use and transmission cross borders.

A distributed system seems natural for solar-powered electricity production: A solar energy electricity production system is highly modular and can be implemented for any capacity. Additionally, it can be deployed anywhere (e.g., as a building-integrated solution) [26].

3 Policies, Development, and Current Research

Recent best-practice examples regarding general energy policy were identified by the International Energy Agency (IEA) in 2013. Among the members of the IEA are those employed by Canada, the Czech Republic, Germany, the Netherlands, Sweden, and the United States, among others. Increased energy efficiency and the use of renewables, in accordance with, for example, the European 2020 targets [27] and international goals for reduced GHG emissions [28], are characteristics common among the highlighted policies. Increased competition in the electricity market is another focus in several countries [29]. Austria, Denmark, the Netherlands, Norway, Sweden, and Spain are highlighted as best-practice examples for actions aiming at an increased use of renewables. For example, Denmark aims at a full conversion to renewable energy by 2050, with wind energy covering 50% of the Danish electricity consumption by 2020 [30].

The need for grid development was identified in 2010 in the IEA technology roadmap for photovoltaics, which suggests a scenario of grid parity by 2020 through the implementation of effective policies. The vision is that 'utility-scale PV could become competitive in the sunniest regions by 2030 and provide 5% of global electricity by 2050' [31]. Currently in the United States, half of all new electricity production derives from PV panels. [32]

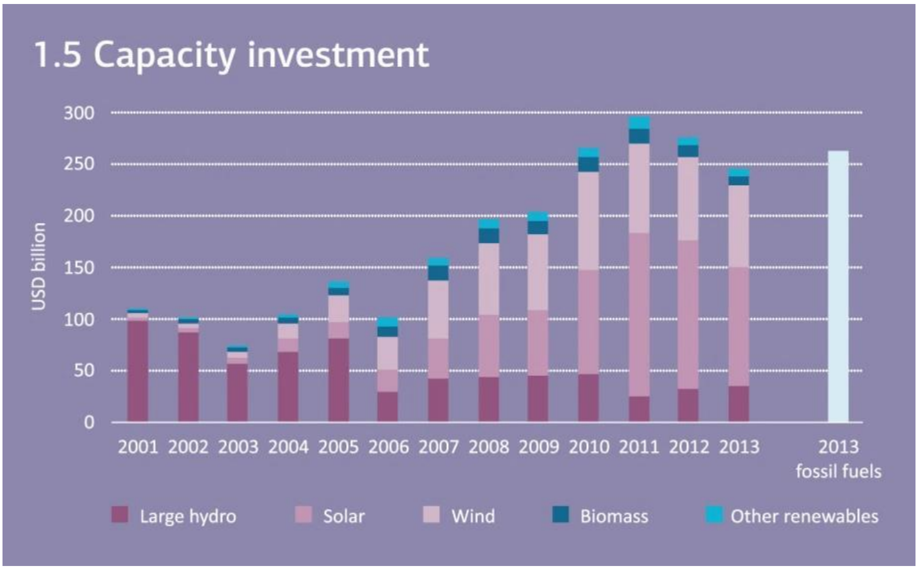

Fig. 7. ***Capacity investments in renewable energy, 2013. Investments in solar technology have increased most during the past 10 years. Asia, especially Japan and China, accounted for more than half of the global increase in photovoltaics in 2013. [33]***

On a global scale, China is currently in second place regarding amounts of installed PV panels, with 20 GW. Germany takes the lead with 37.5 GW [32]. Similar steps have been taken by the Indian government with respect to the use of solar power as a backup during power outages. Global capacity investments in renewables are illustrated in Figure 7 and development targets for 2020 in Figure 8.

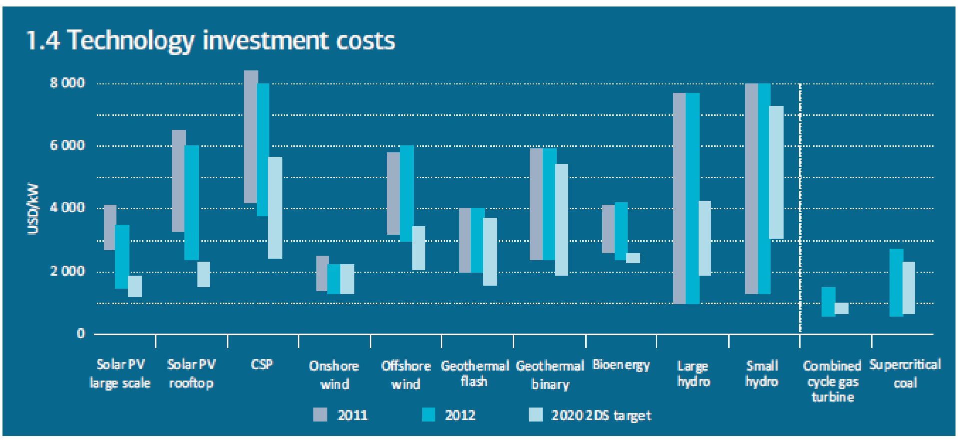

Fig. 8. ***Development of technology investment costs and targets for 2020 [39]***

3.1 Steps Forward

An incrased use of PV-based electricity requires new and innovative energy policies.

The current Dutch policy is a forerunner example of a technology-neutral approach where different renewable technologies compete for subsidies to cover extra costs for producing renewable energy—the least expensive technologies are allowed to apply first [34]. Competition is utilised for the benefit of sustainable development, acting as an incentive to lower the costs of technologies.

The Spanish situation illustrates the need for international collaboration. Spain has more than 2,000 facilities producing electricity from renewable energy sources, mainly wind and hydro power but also solar. However, the border situation with France highlights the importance of the international exchange capacity of electricity to even out fluctuations in production from renewable energy sources [35].

To accelerate the global deployment of solar-powered technologies, the IEA has identified the following four main areas for policy interventions:

1. long-term targets/policies including incentives to accelerate market competitiveness;
2. improved products and components, financing models especially for rural electrification, training and education;
3. continued technology development and increased research and development (R&D) efforts to improve the cost-efficiency ratio and ensure PV readiness for rapid deployment; and
4. improved international collaboration aimed to advance knowledge transfer to emerging and developing countries. [36]

Investments in research are another step to further the use of developed technologies and bridge the gap from innovation to market for technologies using renewable and solar energy. Exemplary programmes have been initiated in France, Italy, and Korea [37]. The IEA has identified the following roadmap for advancements in PV-related R&D:

1. Increase public R&D funding, 2010–2020.
2. Ensure sustained R&D funding in the long term, 2020–2040.
3. Develop and implement smart grids and grid management tools, 2010–2030.
4. Develop and implement enhanced storage technologies from 2030 onward. [38]

4 Future of Energy: Visions for an Increased Use of Solar Power

In this section we present three interlinked visions and suggest measures supporting an increased use of solar energy for electricity production. First we discuss the scenarios using 100% solar electricity, including prerequisites and opportunities for using solar energy as a single source for global electricity. However, as described earlier, this vision is dependent on developed transmission, distribution, and storage systems. Possible solutions are presented as the next scenario, the global electricity grid. As we discussed, the current investors in solar power are not the regions that receive the highest amount of irradiation. To change this, the scenario of 'energy for all' presents a vision of how solar-powered technologies could be used for the benefit of an environmentally, economically, and socially sustainable global future by empowering the current nonconsumer markets, such as countries in Africa.

4.1 Solar Energy as Single Source for Global Electricity: The 100% Scenario

Here we discuss the vision of covering 100% of the world electricity demand with solar power. Given the right circumstances, this could be made possible as early as 2030 [40]. Although we focus mainly on energy supply, we acknowledge and indeed emphasise the importance of demand-side energy conservation measures to reduce the requirements and impacts of energy supply.

4.1.1 Resources Needed and Available

The 100% scenario is based on the use of existing and commercially available technology. The production of energy in this scenario is mainly based on PV and concentrated solar power (CSP). Proposed storage technologies, which are already being used on a commercial scale, are compressed-air energy storage (CAES) and pumped hydroelectric (PHE). The distribution of the electricity from remote plant locations to the grid takes place through high-voltage DC lines, which are currently used [41].

The power required today to satisfy all end uses worldwide is about 12.5 trillion watts (TW) [42]. To satisfy this requirement, about 180,000 PV and CSP plants, averaging 300 MW per plant, would be required. In this scenario, solar PV is divided into 30% rooftop and 70% power plant. Rooftop PV has three major advantages over power-plant PV: (1) rooftop PV does not require an electricity transmission and distribution network; (2) it can be integrated into a hybrid solar system that produces heat, light, and electricity for use on site; and (3) it does not require new land area.

4.1.2 Feasibility in Terms of Raw Material Availability

Solar PVs use amorphous silicon, polycrystalline silicon, micro-crystalline silicon, cadmium telluride, copper indium selenide/sulfide, and other materials. According to a recent review of material issues for terawatt-level development of photovoltaics, the power production of silicon PV technologies is limited not by crystalline silicon (because silicon is widely abundant) but by the reserves of silver, used as an electrode [43]. The research also notes that if the use of silver as top electrode can be reduced in the future, there are no other significant limitations for c-Si solar cells. Other research [44] has studied the current availability and anticipated use of raw materials for 23 different types of PV technologies and concluded that with current technologies, there are still a few bottlenecks that might prevent terawatt-scale installations.

4.1.3 Economic Feasibility

In terms of economic feasibility, we look at a variety of factors, including annualised total capital and land costs, operating and maintenance costs, storage costs, and transmission costs. [45]

Table 2 compares the current and future costs of solar PV and CSP in the United States in USD. These costs include generation and distribution using only currently existing channels.

Transmission costs involving long-distance transmissions have not been considered in Table 2. As stated earlier, long-distance connections are required to alleviate the problem of the variability of solar power. Technology, in the form of high-voltage DC lines, is available to accommodate such a transfer. The best estimate known from current research for all new infrastructure enabling long-distance transmission is about \$0.10/kWh. Storage costs, including batteries, CSP, and hydro-powered plants are estimated to be about \$0.10/kWh, at the most. From all of these calculations, it can be concluded that the end-user cost of using only solar-powered electricity is not likely to exceed \$0.30/kWh. Although this is almost double the price of the current fossil fuel–powered systems, with the increasing pressure on fossil fuels, the predicted increase in energy generation costs is also bound to increase (not factored in Table 2). Effects of policies and subsidies also are not included in the final cost.

Table 2. ***Current and future generation costs for solar power (compared with current USD price based mostly on fossil fuels). Social cost includes cost of pollution and climate damage costs.***

Energy technology	Present cost	Cost after 2020
Solar PV	> \$0.20	\$0.10
CSP	\$0.11–0.15	\$0.08
U.S. traditional	\$0.07 (social cost: \$0.12)	\$0.08 (social cost: \$0.14)

4.1.4 Policy Issues

Because solar PV-based electricity is a completely new form of electricity and requires us to redefine the way we currently generate and consume electricity, it is crucial to define new policies and modify existing policies to encourage this change on a wide scale.

The most common type of policy currently adopted to stimulate the production of renewable energy is to cover the difference between generation costs and current grid price [46, 47]. These subsidies have to be gradually reduced to promote innovation and make renewable energy competent. One major economic policy that can make a difference is to reduce and ultimately remove subsidies on fossil-fuel energy systems and taxing fossil-fuel production using carbon taxes. But even more important than subsidies or carbon taxes is the support for the development of necessary infrastructure. Another policy issue is to encourage and educate people about the importance of green energy. Municipal financing for residential energy-efficiency retrofits or solar installations can help end users overcome the financial barrier of the high upfront cost of these systems.

Overall, in order for the vision of a world with 100% solar-based electricity to be possible, the main barriers are (1) current raw materials being used, and (2) policies. With proper measures to overcome these issues, the scenario can be easily achieved.

4.2 The Global Electricity Grid: Transforming the Electricity Markets

'The sun is the spring that drives all. The sun maintains all human life and supplies all human energy. To increase the force accelerating human movement means to turn to the uses of man more of the sun's energy.' —Nikola Tesla [48]

The sun is always available in some part of the world and simultaneously unavailable in the other parts (see Figure 9). However, energy is needed 24 hours a day at any location. In order to utilise sunlight to meet the global electricity need 365/24 around the globe, it is necessary to produce and collect electricity wherever the sun is available and transmit that to other parts of the world where the sun is not present. In order to do that it is necessary to have solar energy plants in different parts of the world. However, the plants alone won't serve this purpose without a global-level grid.

4.2.1 Why Do We Need a Global Grid Now?

It has been 120 years since Tesla powered Buffalo, New York, with 25-mile-long transmission lines from the first large-scale hydro-electric power plant at Niagara Falls. The World Wide Web and globe-wide cellular networks have enabled humankind with the means to establish real-time communication between any two parts of the world. The first machine age has flourished at its peak and has given the platform for the next [49, 50]. An important observation is that the technological evolution is happening at an exponential rate. As a result, the basic requirement to support the upcoming pace of technological advancements—that is, uninterrupted, ubiquitous, and unlimited power—calls for grand planning at the present time. Significant barriers

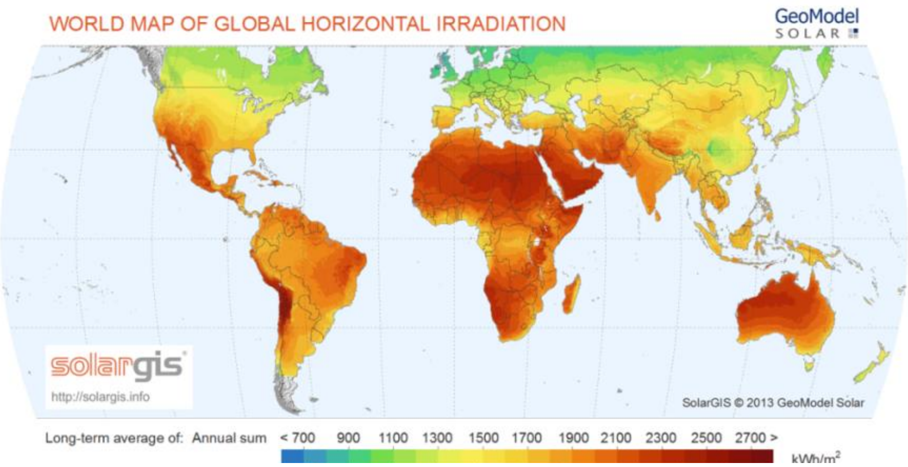

Fig. 9. ***Global solar irradiation map. Solar energy is available everywhere, and especially in the developing countries. Solar power could be an opportunity for a sustainable and equal growth. [59]***

and opportunities for a global-level energy grid are as follows.

4.2.2 Technology

Two different methods are under consideration for long-distance bulk transmission of electricity: high-voltage direct current (HVDC) and the flexible AC transmission system (FACTS). HVDC may be less expensive and have less loss for high long-distance and underwater transmission. One example is the Rio Madeira transmission link in Brazil, which has an overhead length of 2,385 km and uses 600-kV HVDC. However, the challenges resulting from the mesh of many grids need to be overcome. FACTS is a power electronics–based system that is composed of static equipment that provides control of the network and increases the power transfer capability. [51]

4.2.3 Variability

One of the major issues with solar power and also the suggested global grid is the inherent variability of solar power, discussed earlier.

The problem can be overcome by: (1) distributing solar power plants across various regions and interconnecting them; (2) using 'smart' demand-response management to shift flexible loads to match the availability of solar energy; (3) storing electric power for later use; (4) utilising oversized Wind, Water, Solar (WWS) peak generation capacity to minimise the times when available WWS power is less than the demand and to provide spare power to produce hydrogen for flexible transportation and heat uses; and (5) utilising a nonvariable energy source, such as hydroelectric power, to fill temporary gaps between demand and wind or solar generation [52].

All these solutions form a backbone for covering 100% of the electricity demand with solar power. Studies in smaller geographic regions showed how it is possible to reduce variability using dispersed PV sites [46]. One study concluded that with enough geographic diversity, the sub-hourly variability due to passing clouds can be reduced to the point that it is negligible. Oversizing the peak generation capacity is not an economically viable solution, as this requires a lot of additional investment. Research on and creation of new storage technologies are key factors in our scenarios.

4.2.4 Socioeconomic

Europe's dependence on imported energy has risen from 20% in Monnet's time to its present level of 50% and is forecast to reach 70% by 2025 [53]. This need serves as a catalyst to undertake the project of developing a global grid. The current economic recession is an important barrier for the project. However, history dictates that a grand project of this level impacts the economy significantly in a positive way (e.g., the economic boom following the massive transportation investment in the United States) [54].

A global grid will also need to deal with efficient long-term planning procedures, the generation of market-oriented pricing policies, a comprehensive cost-benefit analysis to identify economic solutions, and administration and regulatory issues. Studies suggest that obstacles such as technology per se can be overcome, whereas the real challenge for the implementation of a global grid lies in how to reach consensus among a very large group of stakeholders including generators, system owners, Transmission system operators (TSOs), consumers, and the decision-making entities at all levels of government [55].

4.2.5 Geographic Feasibility and Geopolitical Stability

Globally, 6,500 TWs of solar energy is available over the world's land plus ocean surfaces if all sunlight is used to generate electricity. However, the deliverable solar power over land in locations where solar PV could practically be developed is about 340 TW [57]. CSP could provide about 240 TW of the world's power output. It is less than PV because the land area required for CSP without storage is about one-third greater than that for PV. For implementing the proposed plan, setting up 180,000 solar plants would require only 0.6% of the global land area.

Where to place the solar plants is an issue that encounters various political problems. Putting those aside, according to the Desertec foundation [41], '90 percent of the world's population lives within 3,000 km of deserts', and we have the technology (using HVDC transmission) to transmit power to a populated area with just 3% loss. New transmission technologies are being researched and make this a feasible solution.

However, geopolitical stability is an important factor for such a global-level initiative. If nations are not harmonised internally and externally, no nation will be interested to invest in a project whose safety is a national-level risk. Interestingly, the major reason for geopolitical instability arises from the dependency on and control of fossil fuel.

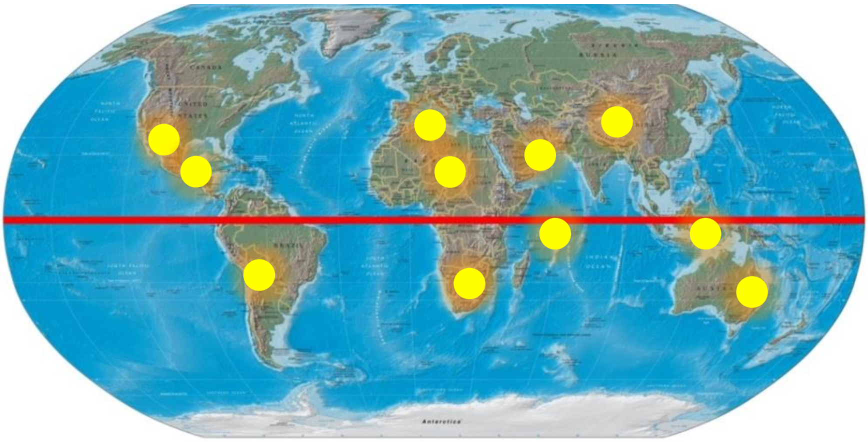

Fig. 10. ***The global electricity grid: utilising areas with most solar radiation for global electricity production [56]***

If the dependency on fossil fuel becomes insignificant through investments in clean energy and a global grid, it could contribute to improving the deteriorating world peace.

The global grid is illustrated in Figure 10.

4.3 Energy for All: Making the World Better by Entering Nonconsumer Markets with Solar-Powered Technologies

Solar power could also support the development of increased global sustainability and equality by entering new energy markets. Globally, 1.3 billion people—18% of the global population—lack electricity [58], and 95% of this population is located in developing areas of Asia or Africa. These areas also receive the highest amounts of solar irradiation (Figure 10 [59]) on the globe. However, solar energy is mostly used in existing energy markets as a replacement for other products. Research and development efforts are also mainly directed toward large-scale solar power unit applications, high-tech solutions such as smart grids and buildings, in the same markets.

Current measures to tackle climate change are also inefficient. The implications are drastic. For example, NASA has listed probable near-future scenarios including decreased precipitation in subtropical areas and decreased water resources in semi-arid areas; for example, in Africa, between 75 and 220 million people are predicted to suffer from a lack of water and a 50% drop in agricultural production by 2020 [60].

Deserts and other dry areas currently cover about 40–41% of the earth's land area; the total area affected by desertification is estimated to between 6 and 12 billion square metres [60]. If all this would be covered by dense greenery we would see an increase of 67% from today—an action tackling both climate change and climate injustice.

Small-scale solutions already exist for solar-powered irrigation pumps (Figures 11 and 12 [62]). However, with large-scale implementation, all areas suffering from or affected

Figs. 11 and 12. ***Solar-driven irrigation pumps, Bangladesh [62]***

by desertification, including the Sahara Desert, could be irrigated starting today. If all deserts would start growing greenery today—food, forests, and biomass—what would this lead to and on what time scale? Food production would start immediately, the growth of biomass with fast-growing species might take 5 years, and the development of dense forests might take a few decades.

What would be the economic consequences if the emphasis of solar technology development would be shifted toward low-cost solutions for everyday needs such as lightning, cooking, and irrigation pumps? IKEA is an example of a business that has proven the concept of gaining and constantly increasing market share by selling increasingly cheaper products for everyday use. Additionally, IKEA has proven the possibility for truly global market leadership with 338 physical stores in 40 countries [63], including, for example, India. Solar energy has the potential to act as a basis for a range of new products and services directed toward current nonconsumers of energy, supporting a sustainable growth based on economic, social, and environmental benefits.

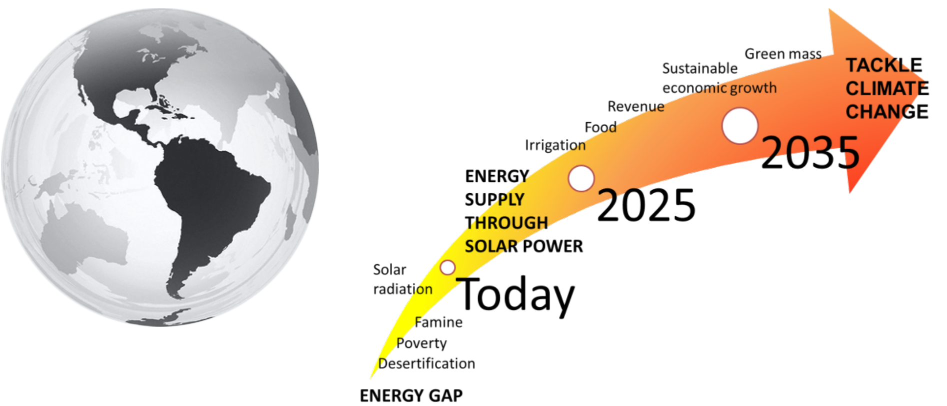

Fig. 14. Vision: solar power as a means to make the world a better place

From this perspective, solar energy could be a resource for future economic growth through capitalizing on social and environmental responsibility. Solar power has the potential for making the world become a more equal, better place (Figure 14). This power could be harnessed for furthering sustainable growth on all levels.

5 Conclusions

Solar power is ubiquitous; it is a renewable resource available for everyone and hence a global opportunity. In this paper, we discuss why solar energy is not currently the leading source of energy in the world. We first analysed current barriers, which include (1) high investment cost, (2) low efficiency, (3) variability, and (4) a lack of political will. We also discussed simple solutions to problems that are currently slowing progress, such as, for example, how variability can be addressed using storage technologies such as compressed air.

We then presented our visions for a future in which (1) 100% of the electricity needs are met using solar power, (2) a global solar-powered grid delivers uninterrupted power to all areas of the globe, and (3) the use of solar innovations in the current nonconsumer markets is increased significantly and subsequently helps to tackle global issues such as climate change.

Our conclusion from the study is that long-term political foresight is currently lacking and is the main barrier to enabling a solar-powered future. Short-term barriers such as a lack of infrastructure or high investment costs can be easily addressed given a strong political will for a greener future. In any case, we strongly believe that solar is the near future.

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Toward Prosperity: Sustainable Energy Solutions for Rural Africa

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Abstract. Sub-Saharan Africa has an abundance of sustainable energy sources, such as solar. Still, 620 million people, of whom most are rural dwellers, live without access to energy. Affordability and energy storage issues remain challenging. Access to energy is essential for the reduction of poverty and the promotion of economic growth and socioeconomic development in the region. Fortunately, sub-Saharan Africa has a leapfrogging possibility, as it could skip the stage of decentralised and fossil fuel–dependent energy production and lead the way in the global fight against climate change. This article reviews technological, financial, and social innovations that could be used in small-scale and rural setting across sub-Saharan Africa. It builds a scenario of life in a rural energy-self-sufficient village in 2035, and then suggests how the potential of innovations discussed could be unleashed to improve lives in the developing parts of the world.

Keywords: sub-Saharan Africa, rural, energy, decentralised

1 Introduction

In sub-Saharan Africa, 620 million people, of whom nearly 80% are rural dwellers, live without access to energy. Providing energy access would improve health-care, education, and economic opportunities, as indicated in Figure 1, as well as increase life expectancy, to mention a few benefits. Although average incomes in the sub-Saharan region have increased and millions of people have lifted themselves out of absolute poverty, defined as living on less than $1.25 per day, sub-Saharan Africa still accounts for 27 out of 36 low-income countries in the world, and these countries rank at the bottom of the Human Development Index [1].

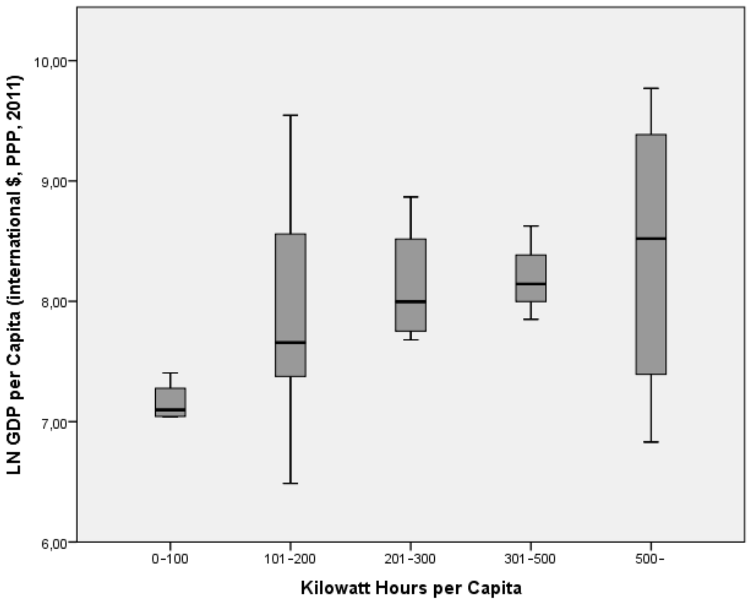


Fig. 1. ***Electrification is likely to be essential for eliminating poverty in sub-Saharan Africa. Gross domestic product (GDP) per capita (purchasing power parity [PPP]) versus electricity production in sub-Saharan Africa (includes only countries for which data was available,*** $n = 22$***), 2011. The bolded line is the median; the lines inside the box represent upper and lower quartiles, and the smallest and largest values are shown with the whiskers (data from [2]).***

However, these very same sub-Saharan countries have abundant renewable energy resources such as solar, hydro, wind, biomass, and geothermal. Nonetheless, at the moment, modern renewables (hydro, solar, wind, geothermal, and bioenergy, except the traditional use of solid biomass) account for less than 2% of the sub-Saharan energy mix. The juxtaposition of these facts highlights the importance of addressing the technological, economic, and sociocultural factors that could, and should, play a key role in unleashing the potential for better energy access—and, ultimately, for better quality of life for millions of people.

Despite the promising recent global developments in, for example, the price of solar photovoltaic (PV) technology, the future of sub-Saharan electrification remains challenging. Even if the energy system in general is expected to expand rapidly, the magnitude of the problem of rural energy access is not likely to diminish in years to come. The International Energy Agency (IEA) forecasts in its probable future scenario, which is based on the continuation of existing policies and measures, that nearly 1 billion people in sub-Saharan Africa will gain energy access by 2040. However, because of simultaneous population growth, 530 million people, mainly in rural areas, are projected to remain without energy access at that date. In the region, contrasting a global trend, the population growth has been split relatively evenly between urban and rural areas [1]. In 2013 the share of urban population was 37% and its annual growth rate only 4.1% [2].

Traditionally, power sector reforms in sub-Saharan Africa have often concentrated on the resolution of problems of the existing electricity infrastructure, rather than the expansion of services to rural and low-income groups [3] [4] [5], as a result of the current supply being both unreliable and expensive for those connected to the grid.

We concentrate on decentralised and renewable solutions. The more sparsely populated and remote the area is, the more likely is the marginal cost of providing decentralised renewable provision lower than that of providing grid expansion to distant rural areas [6]. Furthermore, small-scale options, often commercialised by the private sector, may be the only way forward where there are shortcomings in public policies or institutions [1]. Thus, mini-grid[1] and off-grid[2] systems are the key for delivering energy for rural and remote locations. At the moment, mini-grid and off-grid systems provide electricity to 70% of those having electricity access in rural areas. By 2040, two-thirds of the mini-grid and off-grid systems in rural areas are expected to be powered by solar photovoltaics, small hydropower, or wind [1] [13] [14]. Another possibility is the use of hybrid micro-grid systems[3], which combine fossil fuel (or, e.g., biodiesel) and renewable power generation.

Using the opportunities of renewable sources of energy could make Africa skip one part of the traditional development of energy systems, that of centralised production, and let the continent jump the queue to the newest technologies available. The continent

1 ***Mini-grid*** **refers to small grid systems linking households and other consumers, but not connected to larger regional grids [1] [14]. However, the term *micro-grid* is also used, which can be confusing. Sometimes those terms are used as synonyms, but the term *micro-grid* is used especially in the context of developing countries to refer to very small-scale systems with less than 150 customers [7].**

2 ***Off-grid solution*** **refers to stand-alone systems for individual households or consumers [1] [14].**

3 **A typical hybrid system includes a conventional generator powered by diesel, for example; a renewable energy source(s), including solar PV, wind, or both; and energy storage such as batteries if needed [8].**

had a similar leapfrog experience with the expansion of telecommunication. This example of the success of decentralised services connected with innovative solutions in, for example, local expense-sharing arrangements is the rapid expansion of mobiles in the sub-Saharan, and other developing world, context. From 1960 to 2000, telephone landlines in sub-Saharan Africa grew slowly (3.2% per year) and coverage in 2000 was limited to 1.4 lines per 100 inhabitants. In contrast, mobile phone connections grew quickly after 1993 (55% per year) and coverage had reached 22.5 per 100 inhabitants by 2007 [6]. Furthermore, thanks to the social nature of mobile communications, phones are shared by several people from the same household or the same community, increasing their actual impact even further [9].

We concentrate on solar and algae energy, but briefly review other sources of renewable energy as well. Solar is a suitable solution for rural Africa, taking into account that, on average, bright sunlight is available on 90% of days. In addition, we also discuss an exciting opportunity of algae energy and its suitability to the context of rural villages and small-scale production. We address the most recent developments of these technologies, as well as the challenges and possibilities related to each. Affordability has been identified as the key barrier to adaptation of renewable decentralised technologies in sub-Saharan Africa, and we will address the newest financial innovations and shed a light on the likely scenarios for future price developments of the selected technologies. Furthermore, besides technological and economic barriers, there are also non-financial barriers to access to modern energy. One example is the role of community acceptance, referring to communities' key influence for the success of, for example, small-scale bioenergy projects [10]. Finally, there are also policy-making barriers related to innovation, fluctuating political support, inter-institutional tensions, and policy inertia, among others [11].

To conclude, we believe that the possible leapfrogging of the decentralised energy infrastructure in Africa may provide some insights for the developed countries as well, and the current centralised systems could be redesigned into decentralised systems that are based on renewable and low-carbon energy (see, e.g., [12]).

We will address the following research questions:

1. What are the existing solar and algae energy technologies and innovations that are, or will be, suitable for producing renewable energy in African rural villages?

2. What are the sociocultural and financial enablers or obstacles for the adaptation of these technologies?

2 *Renewable Energy Sources*

Renewable energy commercialisation involves the deployment of three generations of renewable energy technologies dating back more than 100 years. First-generation technologies, which are already mature and economically competitive, include biomass, hydroelectricity, and geothermal power and heat. Second-generation technologies are market-ready and are being deployed at the present time; they include solar heating, photovoltaics, wind power, solar thermal power stations, and modern forms of bioenergy. Third-generation technologies require continued research and development (R&D) efforts in order to make large contributions on a global scale and include advanced biomass gasification, hot-dry-rock geothermal power, and ocean energy [13].

The energy produced today is mainly based on fossil fuels (coal, oil, and gas), nuclear sources, and hydro sources. In the wake of the greenhouse effect and global energy crisis, finding sources of clean, alternative energy and developing everyday life applications are urgent tasks. Therefore, renewable energy sources such as wind farms and solar photovoltaic (PV) and thermal set-ups are increasingly popular as these technologies become mature and companies are urged to reduce their carbon footprint. Decentralised energy production based on renewable sources is a commonly presented vision and solution for future energy needs. Figure 2 shows the distribution of identified renewable energy potential in Africa. As can be seen from Figure 3, the African continent features many sustainable energy resources that are still not used properly to overcome the scarcity of energy.

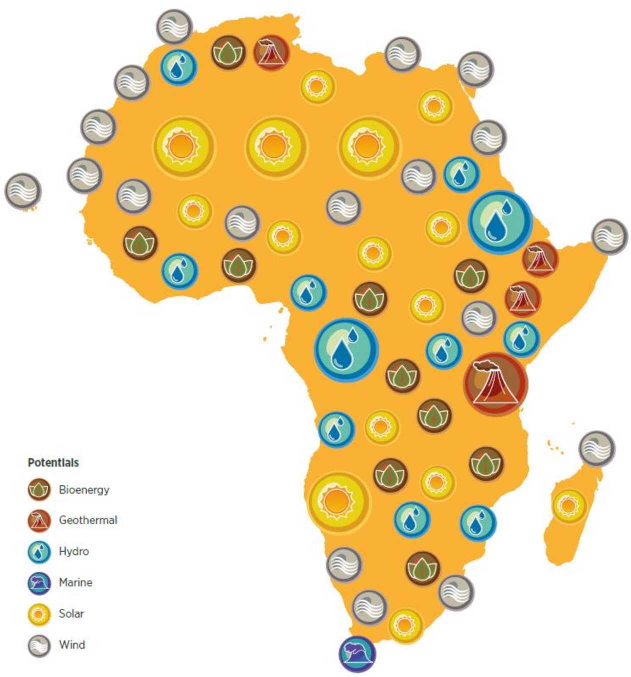


Fig. 2. ***Distribution of identified renewable energy potential in Africa [14]***

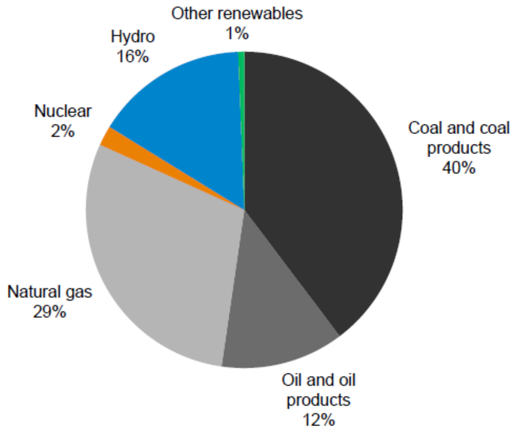


Fig. 3. ***African electricity production [15]***

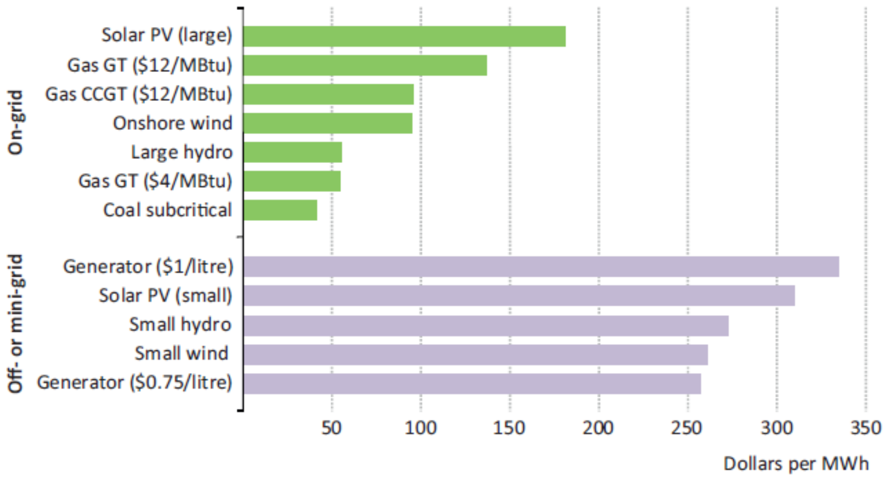
2.1 Current State of Renewable Energy Sources

Renewable energy provided an estimated 19% of global final energy consumption in 2012, and continued to grow strongly in 2013. However, the African continent is far behind in using renewable energy. In this subsection, we discuss the current state of energy generation from renewable energy sources globally, and also from the point of view of the African continent.

2.1.1 Solar Energy

In a project taking place in Germany, the Fraunhofer Institute for Solar Energy Systems is attempting to demonstrate that a solar house can operate completely independently of other forms of energy [16] [17]. This project shows the technical potential of solar energy to replace all environmentally damaging energy carriers in a dwelling. Solar energy is clean, unlimited, and safe. Even when it is converted into electricity through photovoltaic or thermodynamic plants, it does not produce harmful emissions. Solar conversion strategies can be divided into three categories: (1) photovoltaic (efficiency 42.8%), (2) electrochemical (efficiency 3–4%), and (3) solar thermal (efficiency 40.7%). The costs of solar energy technologies have dropped substantially over the last 30 years. For example, the cost of high-power-band solar modules has decreased from about $27,000/kW in 1982 to about $453/kW in 2014 [17].

However, solar technologies have played a limited role in the power sector in Africa. Africa is particularly rich in solar energy potential, with most of the continent enjoying an average of more than 320 days per year of bright sunlight and experiencing irradiance levels of almost 2,000 kWh per square metre (kWh/m^2) annually (twice the average level in Germany) [18]. However, as shown in Figure 4, the average cost to generate electricity from solar PV in sub-Saharan Africa currently exceeds $175 per MWh, which is above the average cost of electricity generated from other grid technologies. Solar PV is much more competitive in off-grid or mini-grid applications, where the main alternative at present is generation fuelled by diesel or gasoline. Where adequate resources are available, small hydro and wind projects can compete with solar PV for off- or mini-grid uses. Solar can also be an effective element in a broader suite of modern energy solutions, such as solar lanterns, ovens, and water heaters.



Notes: Costs are indicative and figures for specific projects could vary significantly, depending on their detailed design. GT = gas turbine; CCGT = combined-cycle gas turbine; MBtu = million British thermal units.

Fig. 4 ***Indicative levelled costs of electricity for on-grid and off-grid technologies in sub-Saharan Africa, 2012 [1]***

2.1.2 Wind Energy

Winds can be defined as movements of air masses in the atmosphere and are an indirect action of solar radiation falling on earth. Winds are generated primarily by temperature differences within the air layer due to differential solar heating [19]. Therefore, wind energy can also be considered as one form of solar energy. The performance and economics of a wind power plant can be determined by the wind characteristics in a specified region, the magnitude of wind speed and its duration, and applied wind technologies. The types of wind turbines are divided into two main categories: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). All particular models of wind turbines gradually developed from one of these categories. Currently, HAWTs have the dominant position in the market, and numerous designs of wind turbines have been proposed and developed for the purpose of reducing total cost and increasing efficiency [19]. According to Abbasi and Premalatha, in 2013 wind energy was considered as the most popular of the cleanest energy sources, because it has the least adverse environmental impacts and is more economically affordable compared with other sources of renewable energy [20].

Globally, the use of wind energy for large-scale electricity production has been increasing faster than that of any other renewable energy technologies over the past decade. Africa still lags behind other regions, and the development of wind energy projects is primarily constrained by lack of precise information about wind potential. In terms of installed capacity at the beginning of 2008, Africa only had about 476 MW of installed wind energy generation capacity compared to the global estimate of

93,900 MW [21]. Countries developing large-scale wind energy projects so far include Morocco, Egypt, Tunisia, South Africa, and Ethiopia.

2.1.3 Biomass Energy

Another interesting alternative energy source that can also be classed as a 'renewable energy resource' is the development of biomass and bioenergy. *Biomass* is a term used for any kind of non-fossil fuel that is classified as being organic, biological, or made of plant matter, and that can be converted into a usable energy source. Biomass energy use depends on a number of issues, including geographical location, land-use patterns, preferences, and cultural and social factors. Historically, biomass-based power has been generated from low-cost, low-grade waste-fuel streams, such as crop residues and wood chips. Depending on the type of plant, biomass could make levelled-cost-of-energy improvements of up to 48% by 2025, making it close to competitive with coal [14].

The majority of sub-Saharan households rely primarily on wood fuel for cooking and heating. Wood fuel is the main source of fuel in rural areas, whereas charcoal is commonly used in the poorer urban households. However, shortages of alternative energy sources, including electricity blackouts and brownouts, often force even the better-off households to use charcoal. As a response to fuel wood shortages, improved biomass cook stoves have been promoted throughout Africa. However, the level of adoption has been limited due to various factors, including cost, effectiveness in fuel or money savings, and compatibility with user needs.

2.1.4 Hydropower

Hydropower systems use the energy in flowing water to produce electricity or mechanical energy. Historically, small hydropower has played an important role in the development of the region, but since the mid-1960s the emphasis has been mainly on fossil fuel–based electricity generation. Only recently small and micro-hydropower systems are getting attention again from developers and policy makers. There are several ways to harness moving water to produce energy. Run-of-the-river systems, which do not require large storage reservoirs, are often used for micro-hydropower systems. Hydropower is the most efficient way to generate electricity. Modern hydro turbines can convert as much as 90% of the available energy into electricity. In the United States, hydropower is produced for an average of 0.85 cents per kilowatt-hour (kWh) [22].

Only about 5% of Africa's hydropower potential of just over 1750 TWh has been exploited. The Inga River in the Democratic Republic of Congo (DRC) holds great potential for hydropower generation in Africa, with an estimated potential of around 40,000 MW. In fact, the DRC alone accounts for over 50% of Africa's hydropower potential; other countries with significant hydropower potential include Angola, Cameroon, Egypt, Ethiopia, Gabon, Madagascar, Mozambique, Niger, and Zambia. Despite the low percentage of use, large-scale hydropower so far provides over 50% of total power supply for 23 countries in Africa [23].

2.1.5 Geothermal

Geothermal energy is the energy extracted from the heat under the earth's surface by using an underground heat pump. Currently, technology is available that allows the generation of electricity from these springs. In some areas of the world, this water creates an upwelling through faults. In Iceland, these faults are called geysers, similar to boiling springs. Globally, geothermal electricity generation is currently used in 24 countries, and geothermal heating is utilised in 70 countries [24]. However, geothermal resources are vastly underutilised on a global scale. Geothermal energy has a high yield but has several disadvantages, including a very high implementation cost.

However, geothermal energy is an untapped renewable energy source that is abundantly present in many parts of Africa. The African continent has a potential of generating up to 14,000 MW from geothermal sources. However, only few countries such as Kenya have used it commercially. As of today, Kenya has installed up to 127 MW, amounting to about 17% of the national power supply, followed by Ethiopia with a 7-MW installation [25]. Plans to use the potential of geothermal energy in Uganda, Tanzania, and Eritrea are at different stages.

2.1.6 Ocean and Marine Energy

Ocean and marine energy refers to various forms of renewable electric energy harnessed from the ocean. There are two primary types of ocean energy: mechanical and thermal. The rotation of the earth and the moon's gravitational pull create mechanical forces. The rotation of the earth creates wind on the ocean surface that forms waves, and the gravitational pull of the moon creates coastal tides and currents. Thermal energy is derived from the sun, which heats the surface of the ocean while the depths remain colder. This temperature difference allows energy to be captured and converted to electric power. Currently, ocean energy technologies are at an early stage of development. Commercial markets are not yet driving marine energy technology development. Government-supported R&D and national policy incentives are the key motivation for most technology development and deployment [26].

2.1.7 Algae

Like many plants, algae rely on photosynthesis to harness solar energy as a means to create energy. But unlike many other plants, algae produce fatty lipid cells that are full of oil [27]. This oil can then be used as a source of fuel. Currently, there are two different land-based systems used to grow algae, open ponds and closed bioreactors. Algae production requires a large amount of land that receives adequate sunlight, which can be a limiting factor in some cases. Additionally, water storage and proper temperature control can be very costly. A lot of water is required for an open pond system to be used, and this has an impact on the surrounding environment [28]. The efficiency of this kind of system depends on algae extraction technology. The extraction technology used will vary based on the manufacturer of the equipment. One specific company, OriginOil, specialises in algae extraction and has systems as efficient as

94–97%. Systems like this are ideal to use because there will be very little waste and more return [29].

South Africa's economy creates large amounts of carbon dioxide (CO_2), with more than 75% of the country's primary energy requirement sourced from fossil fuels. The IEA's 'Bioenergy 2009 Annual Report' also states that, in the longer term, aquatic biomass, or algae, could make a significant contribution to bioenergy. The report points out that future-generation biofuels, such as oils produced from algae, are at the applied research and development stage, and still require considerable development before they can become competitive contributors. However, Cape Carotene is a South African start-up biotechnology company that is developing a production process for the manufacture and marketing of natural products derived from microalgae. The objective of its current project is to produce natural astaxanthin from microalgae for the local and international markets using closed-system cultivation technology for better process control.

2.2 Solar and Algae Energy Innovations

With new innovations of solar and bio energy power it is possible to initialise the electrification of a home or village with minimal initial capital. Wind and solar resources alone are abundant enough to provide all of the electrical energy requirements of rural populations, and this can be done in remote and otherwise fragmented low-density areas that are impractical to address using conventional grid-based systems [30].

The decentralised nature of human settlements in the region implies very high distribution costs for conventional centralised power systems. Contrary to popular belief, a large number of rural Africans reside in individual scattered homesteads and not in concentrated villages. Extending power from centralised generating stations to individual homes is a costly undertaking. In this context, renewables and other decentralised energy options are particularly competitive in delivering modern energy to Africa's rural poor [31].

For our outlook of energy solutions in 2035 in rural Africa, we chose solar photovoltaics, because solar is such an untapped, vastly available resource, and recent innovations in that area indicate that the price of producing energy is coming down.

We also look closely at the novel opportunities for utilising algae as energy source, as algae is a very versatile plant allowing energy production from photosynthesis as well as biogas production from the lipids extracted, and biomass. The remaining biomass can be utilised as human or animal food, or soil fertilizer. Algae energy has also a unique feature of being carbon-negative.

2.2.1 3D-Printed Organic Photovoltaics

The cost of photovoltaic power generation is falling sharply due to technological advancements, manufacturing process improvements, and industry restructuring [32]. At the same time, efficiencies are rapidly rising [33]. Developing countries, where many villages are often more than 5 kilometres away from grid power, are increasingly using photovoltaics. In remote locations in India a rural lighting programme has been providing solar-powered LED lighting to replace kerosene lamps [34]. However, the costs of photovoltaic panels, converting the light into electricity, and storing the energy still remain considerable and prevent large-scale adoption in rural Africa.

A new technology to produce solar photovoltaic cells has the potential to revolutionise solar panel manufacturing: Researchers at the Massachusetts Institute of Technology (MIT) believe that 3D-printed solar panels could be roughly 20% more efficient than flat solar panels. 3D solar panels are more precise, are less complex, and weigh less than flat panels. Another benefit is cost. Precision 3D printing could drop production costs by 50% by eliminating many of the inefficiencies associating with the waste of costly materials such as glass, polysilicon, and even indium. The fact that 3D printing can take place just about anywhere should also mitigate the lofty shipping costs. 3D printing can produce extremely thin solar cells, which can be printed on untreated paper, plastic, or fabric rather than expensive glass. Therefore the advanced ability to create flexible solar panels at a lighter weight could have many positive implications for wearable high-tech clothing, radios, and future electronics. This could create some rather unique future opportunities for 3D solar in areas such as automotive paint and commercial/residential buildings, which may incorporate a thin 'solar spray', something that is far less of an eyesore than PV panels on the roof [35].

Organic photovoltaic cells are made up of small organic molecules that act as semiconductors when struck with solar radiation. Interestingly, the molecules can easily be dissolved into a solution and 3D printed into any shape, size, or colour desired. According to researchers at the National Physical Laboratory, the efficiency of the organic panels is 3% greater when the sun is less intense [74].

Although organic photovoltaics are not nearly as efficient at this point as their silicon-based counterparts—they are only able to produce something like 50% of the voltage—major improvement to that output is expected in only a few years [36].

2.2.2 Algae

Various forms of bioenergy can be produced from algae. These include biodiesel through transesterification of the algal lipids, biogas from anaerobic digestion of the algal biomass (after or without lipid extraction), and heat and electricity from combustion of the algal biomass or burning of biogas produced from it. Suitable sources of carbon, nutrients, and energy are key requirements for the growth of algae. The source of carbon can be CO_2 or sugars originating, for example, from agricultural side streams. Nutrients for growth can be either purchased (commercial fertilizers) or waste-derived, such as from wastewater. Energy can be in the form of sunlight or chemical energy from consumption of organic compounds [37]. Figure 5 shows microalgae-based fuel production alternatives. Figure 6 shows how energy is produced.

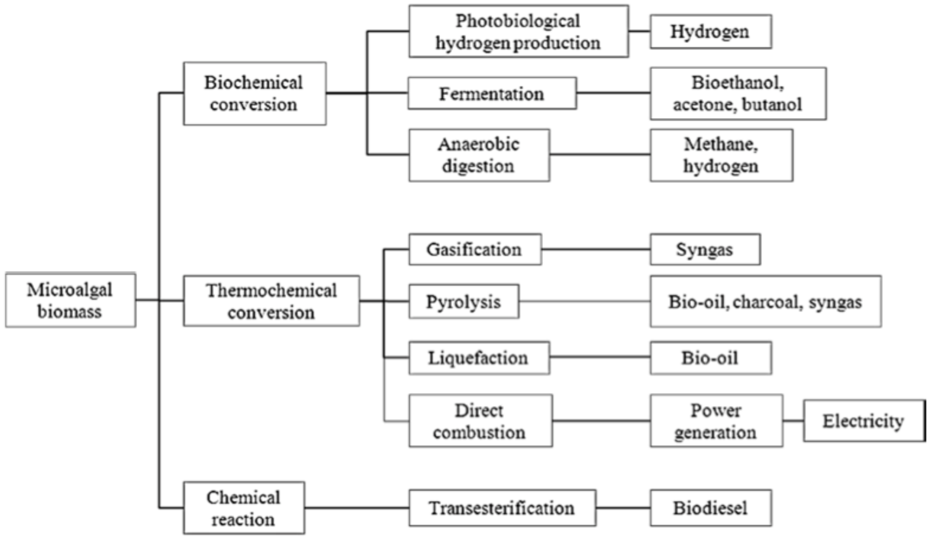


Fig. 5. ***Microalgae-based energy alternatives [38]***

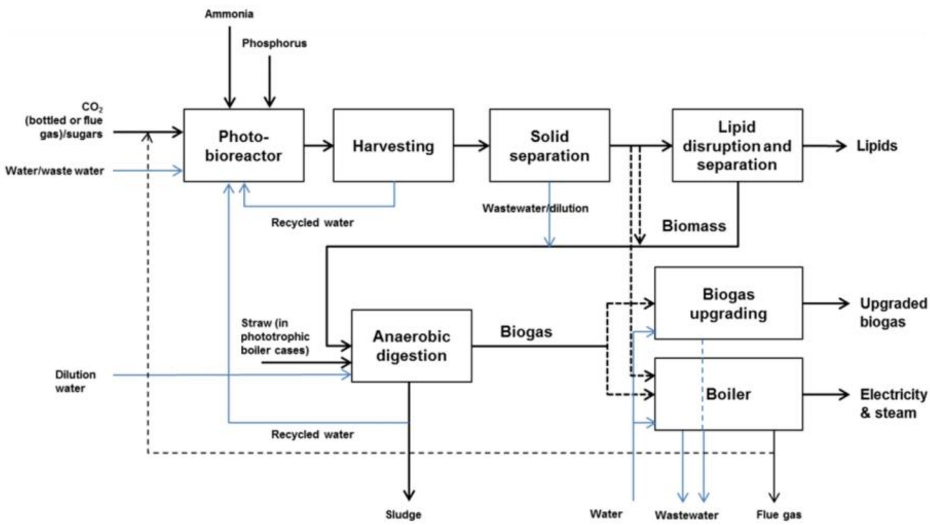


Fig. 6. ***Block-flow diagram of microalgae-based energy production. Dashed lines represent alternative configurations. [37]***

Microalgae production for small-scale energy production, wastewater treatment, or biodiesel production could provide new employment opportunities, in both direct (e.g., plant workers and operators and their families) and indirect (e.g., education, infrastructure development or overall stimulation of the local economy through investments) forms. Algal biomass is capable of producing two or more products at the same time.

Residue algal biomass represents typically 10–50% of defatted microalgae. Industries that could utilise algae-based, high-value products include, for instance, the food industry, pharmaceutical industry, and chemical industry. In these fields non-bulk products can be sold with good margins if the product qualities are unique and/or the brand is widely recognised. These products include, for example, food supplements, medicines, and specialty chemicals [39].

According to Mona Arnold from VTT, some companies utilise every part of the algae. After extracting the energy, the sludge can be utilised, for example, for high-value beauty products or Omega 3 health products. Algal biotechnology could offer surprising applications in the future [40].

2.2.3 Biological Photovoltaics

Biological photovoltaic (BPV) is an energy-generating technology that uses oxygenic photoautotrophic organisms (e.g., mosses, macroalgae, microalgae, cyanobacteria, and purple bacteria) to harvest light energy and produce electrical power [41]. It is hoped that using a living organism (which is capable of self-assembly and self-repair) as the light-harvesting material will make biological photovoltaics a cost-effective alternative to synthetic light-energy-transduction technologies such as silicon-based photovoltaics. The ability of the organism to store energy allows for power generation from biological photovoltaic systems in the dark, circumventing the grid supply and demand problems sometimes faced by conventional photovoltaics [42]. Additionally, the use of photosynthetic organisms that fix carbon dioxide means the system could have a negative carbon footprint. As the system regenerates water there is a closed loop in terms of electron flow (similar to in a conventional photovoltaic system); that is, light energy is the only net input required for production of electrical power.

As biological photovoltaic systems need no input of organic compounds to supply reducing equivalents to the system, this improves the efficiency of light-to-electricity conversion by minimising the number of reactions separating the capture of light energy and reduction of the anode. A disadvantage of using oxygenic photosynthetic material in bioelectrochemical systems is that the production of oxygen in the anodic chamber has a detrimental effect on the cell voltage.

Cambridge University researchers are working with designers to develop algae-powered bio-photovoltaic panels that generate renewable energy from the photosynthesis of algae and moss [43]. Algae and moss are fast-growing organisms that require little more than a bit of sun and water to stay alive. While these organisms are in the midst of photosynthesising, energy can be extracted from them to power photovoltaic panels. Photosynthesis is a process by which plants and algae convert carbon dioxide from the atmosphere into organic compounds using energy from sunlight. The plants use these organic compounds (e.g., carbohydrates, proteins, and lipids) to grow. When the moss photosynthesises it releases some of these organic compounds into the soil, which contains bacteria. The bacteria break down these organic compounds, which they need to survive, liberating by-products that include electrons. These electrons are captured by conductive fibres inside the moss table and put to use. In this way the devices harness energy that would otherwise be wasted. This is achieved using an array of 112 'moss pots', which are bioelectrochemical devices. This means that they convert chemical energy into electrical energy using biological material. The designers believe that this technology could compete with silicon-based solar panels in the next 5 to 10 years. Applications for BPVs are numerous: moss in a table can be harvested directly to power a lamp, an array of algae-powered solar panels can be used for domestic consumption, a near-shore generator can harvest desalinated water, and a forest of solar collecting masts can harvest water to keep energy-generating algae alive [44].

2.2.4 Algae Biogas and Photo-Bioreactors

Algae are also important in the research and development of renewable biofuels. Algae can produce valuable products such as lipids (oils), carbohydrates, proteins, and various feedstocks that can be converted into biofuels and useful materials. The oil produced is suitable for biodiesel with very small modifications. The fatty acid composition is also suitable for production of functional foods and feed, and as raw material for bioplastics and the biochemical industry.

Algae-based biofuel production has a number of potential advantages:

- Biofuels and by-products can be synthesised from a large variety of algae.
- Algae have a rapid growth rate, in comparison with plants.
- Algae can be cultivated in brackish coastal water and seawater.
- Some land areas that are unsuitable for agricultural can be used to cultivate algae.
- Algae can take up high concentrations of nitrogen, silicon, phosphate, and sulfate nutrients from municipal, agricultural, or industrial waste streams.
- Algae can sequester CO_2 from industrial sources. [37]

The overall process of producing high-quality biofuels from microalgae includes two major steps: cultivation of the algal biomass and processing the biomass into a final product (Figure 7).

In order to grow and tap the potentials of algae, efficient photobioreactors are required. The key objective of a photobioreactor is the controlled supply of specific environmental conditions for respective species. Thus, a photobioreactor allows much higher growth rates and purity levels than anywhere in nature or habitats similar to nature. Basically, photobioreactors can grow phototropic biomass even from nutrient-polluted wastewater and from flue gas carbon dioxide. One of the major factors that limit their practical application in algal mass cultures is mass transfer [46]. However, small-scale solutions, which can avoid energy transfer, are interesting.

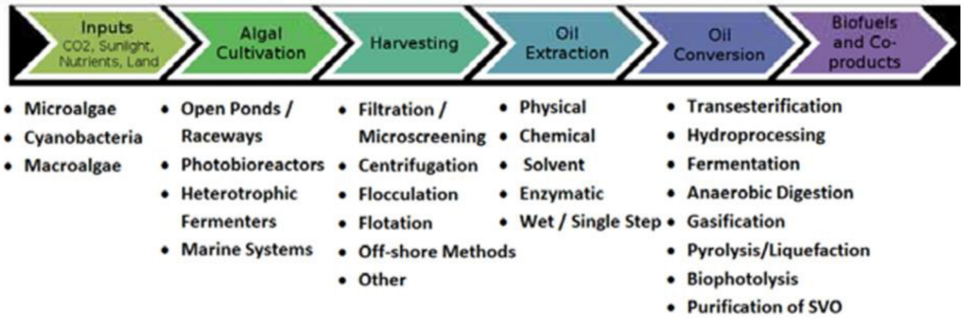


Fig. 7 ***Simplified schematic diagram of major stages involved in producing algal-derived liquid biofuel [45]***

In addition to the energy production potential of the algae, its production systems could enhance rural development through employment opportunities for the landless rural population and farmers and provide new products.

2.2.5 Algae Biogas in Houses

The first algae-powered building, BIQ, has recently been built in Hamburg. Two sides of the building are covered with bio-reactive louvers, which enclose microalgae. These louvers allow the algae to survive and grow faster than they would otherwise while also providing shade for the interior of the building. The bio-reactors trap the heat energy created by the algae, which can then be harvested and used to power the building. The algae are continuously supplied with liquid nutrients and carbon dioxide via a separate water circuit running through the façade. With the aid of sunlight, the algae can photosynthesise and multiply in a regular cycle until they can be harvested. They are then batch separated and transferred as a thick pulp to the technical room of the BIQ. There they are fermented in a biogas plant, so that they can be used again to generate biogas. As a holistic energy concept, the BIQ draws all of the energy needed to generate electricity and heat from renewable sources. BIQ is able to generate energy using the algae biomass harvested from its own façade. Moreover, the façade collects energy by absorbing the light that is not used by the algae and generating heat, as in a solar thermal unit, which is then either used directly for hot water and heating or can be cached in the ground using borehole heat exchangers—80-metre-deep holes filled with brine. This sustainable energy concept is therefore capable of creating a cycle of solar thermal energy, geothermal energy, a condensing boiler, local heat, and the capture of biomass using the bioreactor façade [47].

This prototype ecosystem is very inspirational for an African rural setting in 2035, as it has the potential of solving many problems:

- No land or sea space is required for growing algae, as they can be cultivated on the outer wall of a building.
- Wastewater can be partly purified by feeding the algae with it.
- Algae louvers can provide shade to a building.
- Energy is created in different ways: photosynthesis and biogas.
- The system can produce energy through photosynthesis also in the dark, which makes it an organic solution in storing solar energy.
- Algae grow rapidly and contain a high portion of lipids, which makes a good option for biogas production.
- The remaining biomass can be reutilised in feeding humans and cattle, or in the soil as fertilizer.

2.2.6 Algae Biomass

In our futuristic approach for 2035 we rebuild the rural African house with algae panels providing shade and energy. The algae are then harvested in a common village mini–power plant, where the biogas is extracted via fermentation. The remaining algae biomass will be used for human and animal nutrition, and fertilizer. The solution is implemented with the help of a company providing the architecture of the small house as well as all the equipment and training to run the ecosystem. Government development aid and non-governmental support organisations will serve to guarantee micro-financing of these systems to villages. The surplus of biogas will provide the villagers an opportunity to make a livelihood of this ecosystem, and pay back their loans.

3 *Financial models*

Although the macroeconomic reforms and liberalisation of cash crop marketing in sub-Saharan countries are causing income rise among African rural residents [48], the use of smart financial measures still is required to effectively increase the utilisation of renewable energies in these areas. There is a need for innovative financial instruments that can bypass the existing bureaucracies to provide the masses with ultra-affordable funding options [6] [49] [50]. These instruments already exist and are rather well known. In this section we focus on three major and potentially viable examples among other possible options; that is because those financial models were historically shown to be effective in the African context [51] [56]. The important mutual aspect of all of the options is the possibility to reduce the initial investment shock to customers as much as possible. Moreover, the ease and simplicity of implementation is also among the requirements of every feasible plan, as the locations in discussion are remote and have minimal infrastructure. A detailed explanation of each financial instrument is presented in the following sections.

3.1 Cell Phone Model

Cheap handsets and affordable prepaid cards caused a rapid penetration of mobile phones in the African continent [51]. Abolition of cross-border roaming was another step in the direction of added affordability [52] [53]. Therefore, the repetition of this financing method, which focuses on affordability and usefulness to spread, might also be effective in the energy sustainability of rural Africa.

As Figure 8 illustrates, in this concept, which is an example of centralised provision, investment is done by another entity (company or energy entrepreneur) and is being sold to the members of the community through a very low initial investment cost and affordable periodic prepaid amounts (pay-as-you-go system) [50]. The usefulness of this concept can be magnified through the provision of free mobile phone charging to the entire community, which also can be seen as a way to protect its facilities against vandalism. This concept can be seen as a centralised provision, although the facilities should not be centralised to only a single location.

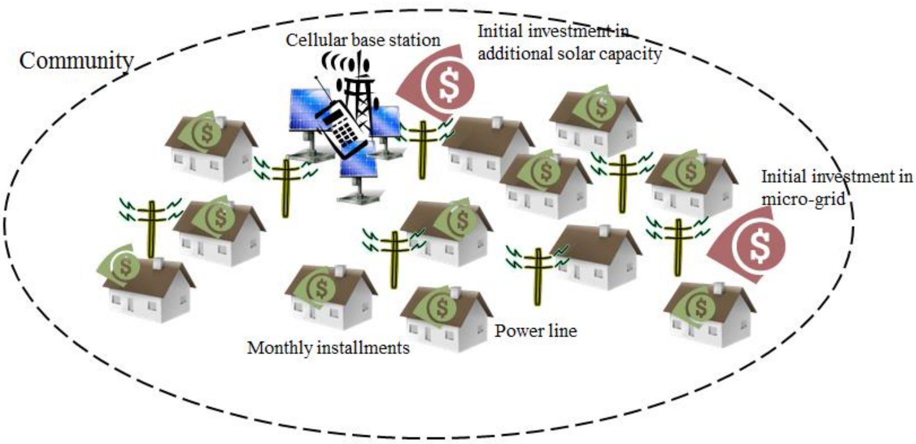


Fig. 8. ***Pay-as-you-go financing model for renewable energies***

The company can utilise some volunteering households as the locations for its energy production facilities in return for some free energy to reduce the land acquisition costs and also reduce the possible vandalism; however, this should be done with care to choose trusted people who are also in locations that can reduce the amount of wiring needed to reach other consumers.

Among the possible companies that may be able to provide this service are the cell phone base station operators. To provide cell phone coverage to rural Africa there is a need for the installation of base stations close to the community. Each station requires 2.75 kW of electricity to run; however, the solutions that have been already developed to power such equipment (e.g., Inala company power management systems) are able to produce excess amounts that not only are enough to recharge the community's cell phones but also to be used for other types of consumption [51]. As currently the mobile phone coverage in African continent is standing at around 70%, it seems a viable solution for the communication service providers to enter the electricity provision business in decentralised settings [55].

3.2 Micro-financing for the Masses

Micro-financing, which won Dr. Muhammad Yunus (founder of Grameen Bank in Bangladesh) a Nobel Prize, has shown to be highly successful in the eradication of poverty and in empowering women in developing economies. It potentially can also be effective for the spread of renewable energies in rural Africa. As Figure 9 suggests, in this method every household may acquire the necessary ultra-affordable electricity generation facilities from a third-party company through a micro-loan [56]. The third-party firm in this concept has dual roles, system provider and financier, although, in a different arrangement, these responsibilities might be assigned to separate entities with interest in people's well-being and education.

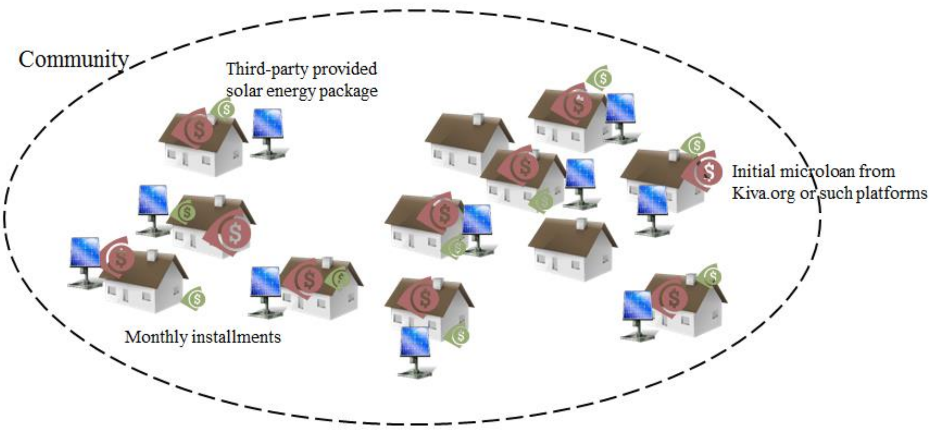


Fig. 9. ***Micro-financing model for renewable energies***

This financing model differs from the previously discussed 'pay-as-you-go' concept in that each household will own a decentralised renewable energy production system instead of relying on a micro-grid. Also, in cases of loan default, systems will be returned to the supplier for refurbishment and resale.

3.3 Assisted Community Cost Sharing

In the cost-sharing financing method (Figure 10), which also has shown to be successful in the rapid spread of cell phones in the African societies [51], a company can play the role of coordinator in aligning the community needs and available financial resources to build the infrastructure. In other words, when a number of households in a community agree among themselves to share the costs of utilising energy production equipment, they can apply for that equipment through the facilitator company, which then will arrange the cost sharing among that group of households and the government or other possible international funding organisations such as the United Nations, World Bank, Global Environmental Facility, development banks, and humanitarian funds [50]. A manufacturing partner will be selected to deliver an affordable solution for the community, which will eventually pay back the remaining costs through a long-term loan. This solution can yield either centralised or decentralised facilities.

The difficulty in this model is that the coordinating entity can take advantage of its role and scam its clients and even fund providers. Additionally, it might be challenging to push the governments to agree on the needs for such funding due to corruption or other political reasons.'

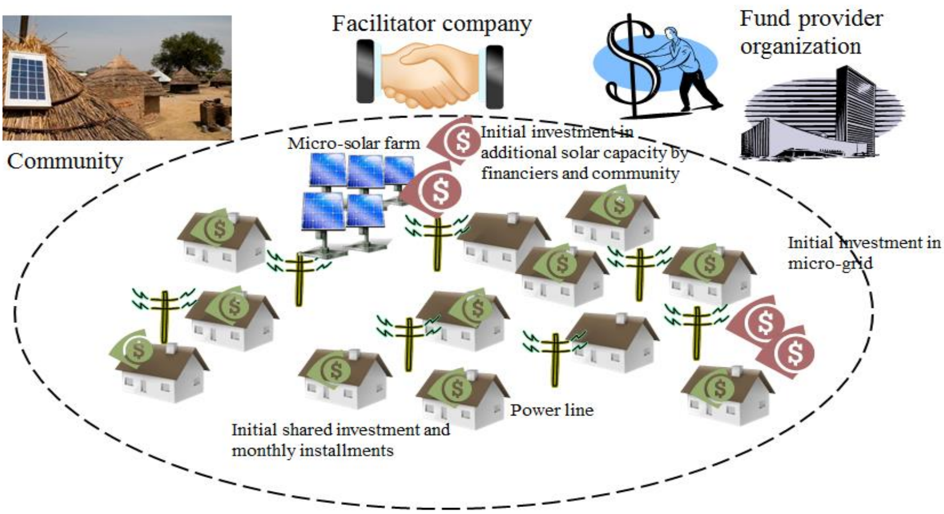


Fig. 10. ***Assisted community cost-sharing financing model for renewable energies***

4 Social Innovations

Discussion on social innovations usually takes a more bottom-up approach, looking at the micro-level barriers to adoption of technologies. The deployment of renewable energy technology such as solar or algae in the African continent needs, undoubtedly, international cooperation as well, as the technological solutions are mainly developed outside of Africa. However, the local context remains critical, and studies suggest that the success of adoption of renewable energy technologies depends on how they are perceived by the community [57] [58]. Community acceptance has been identified as one of the dimensions of social acceptance; the other two are sociopolitical acceptance and market acceptance [59]. For example Eswarlal et al. (p. 342) suggest that the factors influencing community acceptance of bioenergy projects include local energy needs, benefits to the community, other stakeholder roles, proximity to the residents, control over the project, information availability, communication, and relationship and trust. Of these, they identify the other stakeholder roles and proximity to the residents to be important features, in particular, in the context of developing countries [10]. In this section, we first identify challenges that a Finnish solar company has faced in its projects in Africa. Second, we will discuss two examples of social solutions that take into account the local factors and have been proven to be successful in a developing-country context.

4.1 NAPS Solar Systems: Corruption and Misuse as Main Problems

We interviewed Mikko Juntunen, the CTO of Finnish solar company NAPS. The foundations of NAPS are in the oil crisis of 1970s, when the general belief was that we were running out of fossil fuels and, thus, the concentration on renewable energy was well grounded. The company supplies solar electricity systems for communities in places where electricity can improve the quality of life, and it has reference cases from sub-Saharan Africa as well as from other developing countries, such as Sri Lanka and Vietnam.

Juntunen says he has the impression that corruption, stealing, and vandalism are major problems especially in the African village context, and not, for one reason or another, as apparent in similar projects in, for example, Asia. Juntunen gives an example from a Gambian village, where a system was given as a Christmas present to a family to run the village grid for 8 hours a day, independent of the political will, and thus boost the productivity of the whole village. However, when the football world championships in Africa were on television, all the energy was used by that one family to watch the games, leading to the vandalism of the system by envious villagers [60]. Juntunen notes:

> *Over the decades, it has been seen as one of the very big challenges in solar house systems that they get vandalized. This is related to, of course, to the overall situation of the*

societies, whether there is a society at all. [...] People don't bother cultivating the land if they cannot be sure that they can enjoy the crops. [60]

Another challenge mentioned by Juntunen is the educational problem, which the company has solved via a technical solution. The problem is, for example, a situation where the batteries of a system have certain limited hours available per day, and if used more than that, the batteries will deflate, and if kept deflated, the batteries will die and can be used only once or twice. The company has, quite successfully, solved the problem by using modern smart controllers, which are designed to concretely educate users. The controllers alert the user that the battery is empty before it really is, so that users will recharge it. When users learn the correct download style, the buffer is gradually increased, and the batteries can be used for a longer time [60].

4.2 Barefoot College: Everyone Can Be a Solar Engineer

One example of social grassroots innovation that is based in the village and managed and owned by those whom it serves is a model developed by a non-governmental organisation called Barefoot College, established in 1971. The organisation provides basic services and solutions to problems in rural communities, with the objective of making them self-sufficient and sustainable. Barefoot's model is to educate the poor via hands-on-learning, which lets them gain the basic skills they need to provide to their own communities a vital service, such as electricity. One of these 'Barefoot solutions' is the delivery of solar electrification. The idea is to pioneer solar electrification solutions in rural, remote, non-electrified villages. According to the programme's website, it has proved that both illiterate and semi-literate men and women can fabricate, install, use, repair, and maintain sophisticated solar units through basic knowledge sharing and hands-on practical training [61].

The founder of Barefoot College, Sanjit Roy, highlights the benefits below that of energy production, which could be also called positive spillovers. In the following quotation he is describing the benefits of a Barefoot project in the Himalayas where 209 villagers were chosen to go to Barefoot College to become barefoot solar engineers (BSEs):

While improved lighting and heating is a great benefit, another priority is generating employment through the use of solar energy. The BSEs have been trained to fabricate solar water heaters and to use solar energy to dry vegetables. Solar powered spinning wheels have given employment to over 200 women. Ten solar power plants of 2.5 kW each, installed at the rural electronic workshops, have provided power to fabricate charge controllers and inverters. Solar water pumps lift water from the rivers to regenerate wastelands. The BSEs have constructed solar passive houses that retain the heat of the sun when temperatures dip below freezing. In the mountains, these houses serve as schools so that children can go to school even in freezing weather. [62]

However, one can also speculate whether the core idea of Barefoot College, providing practical skills instead of certificates, could lock the people to their villages, as the certifications are probably useful if people want to benefit from the knowledge outside their community, for example, in urban areas. Nevertheless, Barefoot College seems to successfully follow the participation-to-development approach, which refers to enlarging the capacity of socially and economically marginalised individuals and involving them in decision making over their own lives [63] [64].

4.3 Energy Cooperatives: The Power of Local and Shared Ownership

Another idea, partly social and partly financial, is energy cooperatives. According to the World Bank, rural electrification through cooperatives has been successful in countries where institutions are reported to be weak and corruption commonplace [65]. Indeed, many of the sub-Saharan countries rank at the bottom of the Failed States Index [66]. Rural electrification via the energy cooperative model has been very successful in, for example, Costa Rica, where over 98% of the nation's population has access to electric power, which the International Labor Office (ILO) claims to be due to the country's cooperatives, which have been active since the 1960s [67].

Cooperatives can be defined as democratically governed businesses that are motivated by socially orientated goals of local development and closely regulated by their consumers. If appropriate financial and institutional support also is offered, socially oriented cooperative businesses can be a willing, efficient, and effective means of extending and managing rural electricity services. The crucial success factors of cooperative-led delivery are improvements to service, the opportunity for micro-financing, and a sense of empowerment that can lead the community to endorse the approach long-term. One of the possible pitfalls of cooperative models is growing too big: The cooperative might find itself having to service and collect tariff payments over a vast area with poor road infrastructure and limited personnel when wishing to significantly expand the service area so as to further its social goals, increase its revenues, and take advantage of economies of scale [68]. Additionally, another benefit of cooperatives is their ability to operate outside of government control, which should be particularly useful in states of political upheaval, as is common in sub-Saharan Africa.

An example of an energy cooperative in sub-Saharan Africa is the Tanzanian Urambo Electric Consumers Co-operative Society (UECCO), founded in 1993. It is an independent rural cooperative that has established a local mini-grid and maintains its own power generation equipment and serves approximately 200 co-op members via its mini-grid. One of the problems in the model has been that the consumers are reluctant to pay more than is absolutely necessary to maintain the service and that any proposals for accumulation of funds for 'future needs' are met with scepticism. This highlights the essential need to have the affairs of the cooperative as transparent as possible. However, even if the model has some problems, UECCO shows that rural villages have a substantial capability available for local ownership and operation of modest electrification investments [69].

Another example is the Kitonyoni solar power plant project in Kenya, development of which is supported by the Energy for Development (E4D) Network. The community contributes to the project and is responsible for the operation and maintenance of the plant. Income is generated for the cooperative through shared ownership and local sales of electricity, which also finance capital cost. The project has provided up to 3,000 local people with electrical services, and services such as food refrigeration, lighting, and phone- and battery-charging facilities [70].

5 *Scenario: Life in an African Rural Village in 2035*

It is Wednesday morning; Djenabou is sleeping in a dark, cosy room with her younger brother and mother. The air is still humid but getting hotter as the sun starts to rise. The wet season is nearing its end late in October. The house they live in has walls incorporating microalgae louvers that produce fuel used as energy and leftover biomass that the family uses for cooking, to feed the cattle, and as fertilizer for the soil of the village's shared cultivations. The old village of Agnam-Goly, where Djenabou was born in 2015, in north-eastern Senegal, founded in the 16th century, is a rural setting of about 5,000 inhabitants.

Djenabou wakes up to her alarm; it's 7 o'clock. Her brother Boubacar, a 15-year-old student, and her mother stay for another bit of snooze. She walks to the kitchen, switching the light on, as it's still slightly dark—the sun rises year round at 6:30– 7:30 AM in these latitudes. The electric light is something Djenabou takes for granted, certainly, whereas her mother very well remembers the time when working at home was quite restricted to the roughly 12 hours of daylight. Fifteen years ago the evenings were still a quiet time for simple tasks, something that has now abruptly changed to a time for chatting with relatives and friends around the world, playing mobile games, and reading the endless algorithm-evaluated news stream about current global events and the local economy. But Djenabou is part of a big web-native generation of young rural Africans and is not at all petrified by the seeming complexity of living in a free world stripped of absolute truths and authority.

She grabs some tomatoes, dates, and peppers from the aquaponic system installed on the wall of the kitchen; some milk from the fridge, from a bucket full of what was milked just yesterday by her mother from one of the quarters' shared cows; and some sorghum flakes brought and prepared by her mother, grown in one of the in-village cultivations. She prepares some porridge and vegetables and calls the rest of the family to join her.

Agnam-Goly, like a lot of villages in rural areas of Africa, and not unlike most of the larger cities, has turned to an economy profiting from self-sustainable in-town agriculture and cattle. Adding to traditional farm products is a whole new selection of foods provided by the installation of aquaponic systems, a sort of in-house micro-ecosystem that sustains a closed circle of aquatic and plant life. Some households enjoy extra variety and nutrients in their diet from delicacies 3D-printed of insect protein, but the method hasn't gained widespread popularity because many consider food consumed in its naturally occurring shape to be a virtue. This shift in food production has resulted in large areas of land being returned to their natural wild state, as vast but inefficient agricultural fields have disappeared. In unison with this are large areas of forests regrowing, as biomass energy from tree cutting became obsolete almost two decades ago.

Sub-Saharan Africa has taken the surprising, but in hindsight, quite obvious leapfrog to decentralised sustainable energy. What happened during the past 20 years was Africa's black swan surge to a functioning, self-sustaining society consisting of networks of highly autonomous cities and villages. National frontiers in the continent have mostly been abolished, and social identity is anchored in attributes such as natural geographic entities and cultures, not totally unlike in pre-colonial times. This shift was allowed by Africa's adaptation to the possibilities offered by a combination of 3D-printed solar panels, mobile pay-as-you-go financing, and photovoltaic algae energy systems.

Djenabou dresses up for the hot autumn weather in an outfit designed by herself together with a few friends and manufactured at Agnam-Goly's 3D-print lab. She spotted her shirt design on someone the other day on a vlog from Santiago, a coincidence resulting probably from her habit of submitting her designs to an ever-growing public library of online 3D-design templates covering everything from fashion to household items, spare parts, health-care utility, decoration, endless modifications of historic tribal art, mobile phones, food, vehicles of all types, and now even houses.

She walks a couple of blocks to the Agnam-Goly Center for Nomadic Autonomy, where she works one or two days a week in collaboration with members of the Wodaabe people who live in the surrounding Sahel area. They develop solutions for the Wodaabe to adopt portable photovoltaic applications in order to help them develop a health-care system suitable for nomadic requirements, thus helping the tribes to sustain their centuries-old independent pastoral lifestyle without compromising their cycles by having to stay near permanent settlements repeatedly.

The fact that 3D printing has made the production of solar panels extremely affordable means that even the most secluded and distant tribes are now starting to experiment with new energy solutions. Although in 2035 nomadic tribes are at the tidal wave of change, more permanent rural settings have already gone through major shifts in education, independent food production, independent governing, and health care—all due to the near-zero cost of energy production.

After about 3 hours of work with nomadic technologies, Djenabou joins her friends for lunch at the market square, a vivid place for trade, bringing an array of producers of food, appliances, and ideas together daily to mingle and bargain with customers and a local squad of small investors. After lunch she stays lounging in the shade of an acacia tree around a more peaceful corner of a little garden next to the market square. She connects her tablet to an online meeting with doctoral students of Finland's Aalto University course Bit Bang 27 who are researching future scenarios for sustainable food production and want to learn about cassava cultivation in aquaponic systems. Her native Tukulor dialect of the Fula language is real-time translated to Finnish, Swedish, and English.

The conversation turns to solar panels, which are now entering the Finnish realm as well. The production of nuclear and fossil became more and more unstable after the market price of solar panels dipped to a global permanent low. Nuclear and fossil are now heavily dependent on subsidising, and the situation in Finland is made more complex by the country's dependence on the fluctuating Russian market and political stances. A development of the past decade, the African continent was largely a predecessor in adapting decentralised photovoltaic technology not because of its sunny climate, but because at the time of the plunging prices, it lacked investments in long-term, expensive, high-tech solutions such as nuclear power. The existing coal power and utility companies in Africa went quickly bankrupt after 2020 when affordable solar power systems started to enter the African market. This trend, a decade later, is now affecting Western countries as well, only slightly slowed down by some governments' attempts to subsidise coal and nuclear and the last of the lobbyists against solar power.

After the online meeting and a promenade at the bank of the Senegal River, Djenabou returns home. It's 6 PM; the sun is setting. Her mother cooks fish collected from the aquaponic tank. The side dish is a remoulade made of algae, a by-product of the algae power system their neighbourhood is now experimenting with. After dinner she goes to her room to do some homework for her online studies on programming and prepares a presentation on Fulani history for school for tomorrow. Later she watches some music videos by Ghanaian techno artists, watches a reality TV show about life in a Chinese colony on Mars, reads a few pages of Dostoyevski and goes to sleep.

6 Conclusions and Recommendations

According to futurist Pentti Malaska's thinking, all societies follow the path that consists of transformation from a society of basic needs (characterised by the dominance of the agrarian mode of production) to a society of tangible needs (industrial mode becoming dominant in production), and further to a society of intangible needs (service mode becoming dominant). A decentralised mode of production, as the main logic of industrialisation, is typical of the second phase [68]. As the example of mobile technologies shows, Africa as a continent is capable of skipping stages of development, namely, coverage via landlines. The possibility of leapfrogging is also demonstrated in the innovativeness of the Estonian information society. Less developed countries do not need to repeat all phases of development that, for example, their neighbours or more developed countries have gone through.

The mobile revolution democratised communication in Africa, and helped the continent to move toward decentralised production of information; the consequences were seen in, for example, the Arab Spring. Mobile phones are also revolutionising other sectors, such as banking, retail, and education [72]. The key success factors behind the mobile revolution in the continent can be speculated, but those were, undoubtedly, related to low-cost innovations not only in technology but also in cost sharing and easiness of use. Making an analogy between mobile phones and energy, it can be concluded that the provision of energy also could skip the centralised and fossil fuel–dependent phase and move straightforward into the decentralised phase.

Expanding the usage of solar energy is the most natural future development in Africa's electrification. However, the cost of the equipment—whether it be solar photovoltaics, solar thermal energy, or artificial photosynthesis—and challenges in the storage of the energy are barriers to mass adoption in rural Africa. In addition to solar energy, we have also looked into a so-far untapped potential energy source: algae. This organic energy source is dependent on sunlight and water. Considering the climate change issues, this energy source can be part of the solution globally as well, as it can consume more CO_2 than its energy usage will produce. In addition to its carbon-negativity, it can participate in purifying wastewaters and can create energy in a multitude of ways (bio-photovoltaics, biogas, and biomass).

The affordability of renewable and decentralised systems will remain challenging also in the future. However, the initial investments required for the electrification of rural Africa can potentially be picked up by different entities in three likely payback settings. Renewable energy companies can exist in a pay-as-you-go system, where the energy is produced in a micro-grid for each community and sold to them according to their individual needs with affordable prices. Micro-financing through banks or facility providers is another potent solution to bring sustainable energy production capability to every household in a decentralised manner. And, finally, an optional solution is cooperation among communities and local or international fund providers, such as governments or the United Nations, to share the initial costs of the electrification projects. The community then will pay back the borrowed money in a long-term loan setting with low interest rates. We believe that the focus of international efforts should emphasise small-scale and community-level efforts, instead of national-level and capital-intensive efforts. Through these funding mechanisms we see a bright future for the renewable energies in Africa, which will further accelerate the economic growth in that region and spark a renaissance in communities' well-being and education.

However, there are also uncertainties in the future development of both algae and solar energy. Climate conditions and the availability of CO_2, other nutrients (nitrogen and phosphorous), and water resources greatly affect algae productivity. In addition, land considerations, such as topography, use, and stewardship, help define the land available for algae production. The perceived availability of water (of low quality with few competing uses), CO_2, and non-arable land resources in suitable climates is a significant driver for the development of algal biofuels. From the perspective of producing biofuels, the most important issue is that where co-products are used in the human food chain, producers will have to show that the products are safe. Where algae are harvested from the wild for human consumption, the principal concern is contamination from undesirable species. From an economic perspective, algal toxins may be important and valuable products in their own right with applications in biomedical, toxicological, and chemical research. Solar energy, again, especially if the promise of 3D-printing of efficient solar panels at a very low cost holds true, is subject to revolutionising life in both big cities and rural settings.

Futurist Ray Kurzweil notes that the use of solar power has been doubling every 2 years for the past 30 years, as costs have been dropping. He says solar energy is only six doublings—or less than 14 years—away from meeting 100% of today's energy needs. Energy usage will keep increasing, so this is a moving target. But, by Kurzweil's estimates, inexpensive renewable sources will provide more energy than the world needs in less than 20 years. Even then, we will be using only one part in 10,000 of the sunlight that falls on the Earth [73].

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Energy in Science Fiction Literature

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Abstract. Science fiction stories construct near-future, far-future, or fantastic worlds in which science, technology, and society intersect. These worlds can contain seeds of truth, and fiction can turn into fact later on. The genre can be useful when extrapolating current trends and shedding light on risks and opportunities involved. In our study, we research how energy is viewed in science fiction literature. We look into the intersection of fact and fiction, and scan for past predictions and identify possible futures in the sector. As our research material, we have selected a spectrum of science fiction books. Recurring themes include energy harvesting, space solar, and antimatter. These themes span the whole applicability spectrum: space solar is on the verge of commercial application, whereas antimatter remains a futuristic vision. We conclude that science fiction is a useful asset for scientists and companies, and the possibilities to use it in innovation activities should not be overlooked.

Keywords: science fiction, future studies, energy scenarios, space-based solar power, antimatter, energy harvesting

1 *Introduction*

The advancing society of 20th century was mainly powered by unsustainable energy production from fossil fuels. With the start of the new millennia, the disadvantages of oil and its relatives are becoming more prominent and the search for alternative solutions grows more determined than ever. Although oil as a transportation fuel appears unbeatable, the rest of societal functions require increasing amounts of high-grade energy, electricity. But in order to satisfy the energy demand of the increasing population, a single power source alone cannot overthrow fossil fuels, but instead, all potential energy forms need acute attention. There are multiple pressing questions to be solved. How will we provide the energy for an ever-growing population? How can we produce it in a sustainable manner? What are the far-reaching consequences of our energy-related decisions of today?

Popper says in his critiques of historicisms that forecasting the future is, in principle, impossible, as we cannot know what will be invented: if we knew, those innovations would be already here [1]. However, for example, Niiniluoto [2] has counterargued that it is, at least in some instances, possible to make apt guesses on what will be technologically possible, even if one cannot know how those possibilities will be actually implemented. He sees Leonardo da Vinci's bicycles and flying techniques (16th century), Cyrano de Bergerac's machine for moon travels (17th century), Louis-Sebastian Mercier's projection on future Paris (18th century), and Jules Verne's stories about submarines and rockets (19th century) as forerunners to whom the science fiction stories of today can be seen as a continuum.

This article indeed argues that science fiction literature is a particularly suitable genre where one should look for answers to the questions about the future of energy. Accordingly, definitions of science fiction highlight its role as a bridge between today's science and the future's world. Thacker [3] defines science fiction as "a contemporary mode in which the techniques of extrapolation and speculation are utilized in a narrative form, to construct near-future, far-future or fantastic worlds in which science, technology, and society intersect." Nauman and Shaw [4] give a broader definition of the genre by saying that it is "[a] science-based form of literature that is not true to the reality of today, but may become so in the future."

Energy is an extremely suitable theme for looking into the interconnections between reality and fiction. Spaceships powered by mysterious fuels, protective energy fields, and other technological innovations have always been self-evident in science fiction stories, and there are many examples of inventions that no longer appear as far-fetched as they were for the readers of the same books, for example, 50 years ago. Also, in the realm of science fiction, alternative and abundant energy sources have dominated more traditional energy sources such as fossil fuels, which is a desirable, and also probable, trend for the energy sources also in reality.

The purpose of our paper is to speculate whether science fiction could play, or has played, a role in forecasting energy-related developments and innovations. Furthermore, we ask if the full potential of the genre remains untapped—could it be used more in inspiring energy-related research and innovation activities? As the availability of affordable energy sources is becoming limited in many societies, we are proposing that no source of new solutions in this field should be overlooked. We demonstrate how science fiction can, indeed, provide some possible developmental ideas and also help to estimate the long-term implications of new technologies. Visiting a fictional future can be mind-opening not only for a researcher developing energy technologies but also for an entrepreneur looking for new opportunities. Our aim is to establish a link between cultural products and societal advances in the energy field.

We start our study by stepping into the common ground of science fiction literature and science: future studies. We then look into energy themes in science fiction literature, and give an overview of the examples of energy innovations that have first appeared, at least in some form, in science fiction literature and become reality later on. From these, we next discuss energy harvesting, space solar, and antimatter in a more detailed manner. Finally, we use the science fiction literature we have reviewed as fuel for possible scenarios on the global status of solar energy in 2060.

2 Science Fiction and Future Studies: Visualizing the Future

By definition, science fiction and future are intertwined. As the inspiration of the science fiction genre is rooted in real technological and scientific developments, the stories possess a great variety of predictions for the existing directions. This pool of scenarios provides an excellent mining ground for researchers in the field of future studies. Next we will describe how science fiction and future studies actually evolved together and what kind of applications science fiction has to offer. The two directions of science fiction, utopias and dystopias, are then discussed to shed light on how societal development is viewed in the literature in connection with energy discoveries. We also introduce the reader to a newly developed method called science fiction prototyping (SFP), which is an example of how science fiction can be concretely utilized in creating the future.

2.1 Science Fiction and Future Studies

Science fiction is a place we look to "see" the future [5,6]. Indeed, science fiction has already played a role in the methodologies of future studies for a notable period of time. Future studies, in brief, can be defined as an empirical and scientifically based approach to understanding and knowing about the future. In fact, both science fiction and future studies have a common denominator, namely, H. G. Wells. He is said to be the founding father of future studies, or "futurism" [7], even if he is more commonly known as a science fiction author. According to Wagar, Wells's book *Anticipations* (1902) marks the beginnings of futurism. However, the scientific field of future studies started to develop only in the 1960s and 1970s [8].

Like future studies, also science fiction can be said to be based on today—as future itself does not exist yet, nor can it be observed; one has to predict or understand it through recent developments. Thus, both future studies and science fiction have their role in visualizing the future, or extrapolating current trends and shedding light on risks and opportunities involved. One of the main principles of futures research is taking radical, unorthodox, and unconventional views seriously [9].

Science fiction, indeed, plays a role in some techniques of managing, planning, or creating the future. Coates et al. [10] refer to this when they talk about issues management—that is, a range of techniques used by the commercial sector to identify emerging issues—and highlight that such scanning of the environment allows a company to take a proactive approach toward emerging issues. They suggest that such issues tend to follow a common pattern from an original idea—often in fringe media, science fiction, or art—through detailed research and specialized journals before they take up as public concerns that eventually lead to legislation or changes of behavior. This same idea was brought out by Renfro [11] in his concept of an issue's life cycle, which is a certain type of S-curve. Environmental scanning is another similar tool, or set of tools, used for managing the future, and it is used to indicate emerging issues and trends, or so-called lone signals (early signs of new developments), which can be spotted also from science fiction literature. However, scanning is always biased, as the amount of information available is vast and not everything can be taken into account. One of the typical biases in scanning activities is preference of nonfiction over fiction [12]. Speculative writing is also one of the techniques of future studies and is used, especially, for forecasting purposes, but also for introducing new ideas and innovative thinking.

In addition to more specific techniques or methods, science fiction can also be used to legitimize new ideas in an easily approachable manner. Presenting a future world certainly provides great entertainment value, but it can also be used to investigate or raise important issues in a thought-provoking manner [13]. Sometimes science fiction is used for a kind of enlightenment, as it can, through its popularity, make ideas about the future available to a wider audience [14]. Several scientists (e.g., Goddard, Oberth, von Braun) actually wrote fiction to popularize their ideas. Some authors have recommended using science fiction for educational purposes, to inspire children to grow an interest in, for example, natural sciences [4]. Familiarizing adolescents with science fiction concepts also has the effect of making the predictions self-fulfilling: Some of the dedicated children grow up to be scientists determined to realize their childhood dreams. For example, according to Johnson [15], Arthur C. Clark said that all of the pioneers of astronautics behind the first visit to the Moon were set on that path after reading Jules Verne:

> *Good evening. This is the Commander of Apollo 11. A hundred years ago, Jules Verne wrote a book about a voyage to the Moon. His spaceship, Columbia, took off from Florida and landed in the Pacific Ocean after completing a trip to the Moon. It seems appropriate to us to share with you some of the reflections of the crew as the modern-day Columbia completes its rendezvous with the planet Earth and the same Pacific Ocean tomorrow.* [16]

However, both fields of activity are arguably less respected in the eyes of traditional fields. Science fiction is not an actual science; even if it can be utilized when, for example, using future-studies methods to grasp the future. Sometimes it is ambiguous whether science fiction writers are the first ones to raise questions about new technological developments, or whether they are just popularizing the current concerns. Furthermore, science fiction can use the future only as a "plot device," and there is no quality criterion for the future images produced—not all of the forecasts in the science fiction are accurate or plausible [17]. There are also claims that science fiction has become little more than escapist fantasies [13].

2.2 Energy Utopias and Dystopias

It has been suggested that science fiction is actually not at all about the future, but about casting a light on present issues and directions. For example, George Orwell's *1984*, which, literally, tells about the society in 1984, is said to actually handle the societal developments occurring in 1948, around the date of its publication. Likewise, the current "mood" of society is also related to what kinds of future images or scenarios are produced, at least in the case of future studies, but the same tendency is likely to exist also in fiction writing. Utopianism, positive images of a better future, often results from scientific and technological advances and an optimistic belief in their continuation. However, in gloomier times the more pessimistic or even apocalyptic images of the future, dystopias, tend to dominate [13].

When it comes to the energy question, there are examples of the interconnection between what has actually happened and how it was used as an input in science fiction literature of that era. According to the SFE (Encyclopedia of Science Fiction) database, the invention of the steam engine, leading to Industrial Revolution, also made countless science fiction writers optimists who imagined futures of similarly revolutionary inventions. Likewise, the discovery of X-rays in 1895 led to a situation where unlimited power was casually generated in science fiction stories by invoking magical rays. There was a firm belief in the availability of unlimited power, and thus many of the works of speculative writers in the early 20th century deal with the question of the social responsibility of scientists making such discoveries [18].

However, the common belief in the abundance of energy was shocked by the oil crisis in 1973, and the politics of the Organization of Petroleum Exporting Countries (OPEC) made the belief in ever-continuing progress questionable. The idea of peak oil gained foothold, leading to more dystopian energy images also in the realm of science fiction. The oil crisis is said to have inspired, for example, Wolfgang Jeschke's *The Last Day of Creation* (1981), whose plot depicts the hijack attempt of Middle Eastern oilfields by time travel [18]. From the more recent themes, climate change has affected how the future is seen in science fiction literature, especially in the sub-genre of so called near-future science fiction [19].

> A recent example of how the energy scheme defines the societal circumstances of the story is Ahmed Khaled Tawfik's dystopian novel *Utopia* [20]. In this reversely named novel the main theme is social inequality, resulting from the U.S. invention of a new super-fuel, which takes the place of fossil fuels and makes the Middle East's petroleum reserves worthless, leading to a divided Egypt. In the depicted future, Egypt in 2023 is divided into inhabitants of Utopia and the Others. The small minority living in Utopia have everything, whereas the Others live in poverty, hunger, and without access to electricity. There is no middle class [20]. In *Utopia*, the link between societal development and energy availability is highlighted, and in the lack of a detailed technical description of the fuel, the novel is more of a societal scenario and projection of how the energy source influences the global economy and state of humanity. *Utopia* might be interpreted as a criticism for the current approaches of treating a necessity as a commercial product, which indeed has been seen to lead to societal inequality between the rich and poor.

2.3 Science Fiction Prototyping

In addition to its role in future studies, science fiction has recently been applied in product development and design. Science fiction prototyping (SFP) can be grouped under design thinking. The purpose of SFP is to turn "the co-evolutionary spiral" of science fiction and fact into a concrete method. It was developed and deployed by Brian

David Johnson, a futurist at Intel Corporation, in order to find ideas and approaches for new products by using creative writing. The idea in SFP is to create a short story, typically around 6 to 12 pages, which is then used as a basis for conversation and brainstorming [21]. Wrapping the imagined technology around a story is argued to help people from non-science backgrounds to approach the issue and maybe come up with different perspectives regarding product design, use, or marketing. Although the stories involved in typical SFP are quite long, also a sub-area called micro-fiction exists, where stories are only 6 to 1,000 words long. This is a quick way of collecting ideas in an easily approachable form [22].

SFP can be used for inspiring scientific thinking, and Johnson [21] also introduced it as a tool for emerging technology research. However, he considers that the science fiction prototypes are most useful when they are used explicitly as a step or input in the development process of new products. The common process for creating an SFP story is to first choose the area of science you want to concentrate on and then build a world and a plot around it. The result is then evaluated from a scientific point of view and the perspective of characters in the story, including a description of the impact that the SFP has on their daily lives. In the end, the most important question is raised: What did we learn from the SFP? Here, all the implications of the technology are explored, before turning science fiction into science fact [21]. In essence, the purpose of SFP is to translate the message of future studies into predictions of possible growth areas for companies by bringing the future into current context.

Although SFP started with storytelling and creating narratives, also cultural products like literature and movies can serve as a source of creativity. SFP from existing literature can also be defined as sociocultural prototyping (SCP), which has an additional aspect of exploring the context and reception of the imagined construction of reality. This is intended to project the prototype onto the world of the consumer: an important aspect of innovation is the diffusion of ideas and trends and thus the need to buy the new product. If the story is not created for the company's needs, it also has the advantage of being unbiased, so new business models not related to the company's conventions can prosper. As the literature is already out in the market, potential customers are acquainted with the idea, facilitating the acceptance of the product and stimulating the desire to buy it. Prototyping from existing literature is less common than conventional SFP but nonetheless has great potential to create new business areas [23]. SFP and SCP are focusing on near-future scenarios and might be useful tools also for companies in the energy sector.

3 Path from Science Fiction to Science Fact

Is science fiction just "fiction"? Or does it have any impact on real science? This section aims to answer these questions by looking at references to various science fiction prototypes that made it into commercial, civil, or military applications. There have been numerous cases of applications of science fiction in various domains of research. We first look at the general changes that have happened in science fiction literature and then discuss mentions of energy in greater detail. We explored hundreds of literature works classified as science fiction written during 1600–2014 to get an overview of key areas and developments relating to energy. The list of books and summaries was obtained from Technovelgy [24], a website that provides references to new technologies from science fiction novels. We divided the timeline into eight phases: 1600–1899, 1900–1949, 1950s, 1960s, 1970s, 1980s, 1990s, and after year 2000. Table 1 contains the number of books considered for each time period.

Table 1. ***Numbers of Science Fiction Books We Considered, by Time Periods of Publishing***

Time period	Number of books considered
From 1600 to 1899	36
From 1900 to 1949	228
1950's	146
1960's	130
1970's	75
1980's	78
1990's	73
After 2000	73
Total	**839**

Source: Material collected from Technovelgy [24].

We investigated mentions of a set of keywords in book summaries across time. The keywords chosen were *space*, *Moon*, *robot, nuclear*, *computer*, and *wearable*. These keywords were the most frequently mentioned words in these respective time periods. Figure 1 shows the percentage of books mentioning specific keywords during each period of time. Interesting observations can be made by following the changes in the mentioned themes. The major themes in the early days (1600–1899) were space and the Moon. Afterward, the popularity of the Moon decreased close to no mentions at all. Robots have always been a popular subject, with mentions as early as 1900s, and a peak in the 1950s. The keyword *computer* started to appear in a greater ratio of books in the 1970s, coinciding with the increase of commercial computer applications. We also observed an increased interest in wearables within the recent years, which reflect the increasing level of sophistication in current-day technology, the basis of science fiction literature.

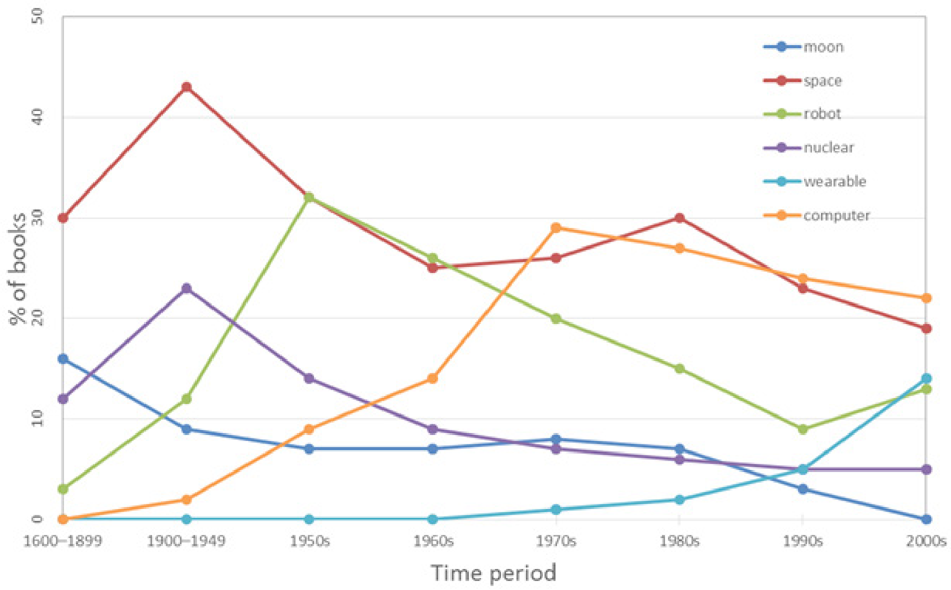

Figure 1. ***Popularity of selected topics in science fiction literature in different time periods. The percentage of books containing a reference to the selected keywords was plotted against the time of the publishing. The number of books considered in each time period is shown in Table 1. The trends show a decreasing frequency of mention of topics such as space, the Moon, and nuclear, whereas computers and robots have maintained or increased their popularity. A newcomer in the science fiction literature is the topic of wearables, which seems to be a popular new topic of the 21st century. Source: Information to create this figure was obtained from [24].***

Next, we gathered mentions of different energy-related technologies from this list of books and looked at when these technologies became a reality. For illustrative purposes, we only chose a subset of technologies mentioned. We positioned these examples into the two timelines in Figure 2. Interestingly, many complicated ideas were proposed decades before the relevant technology was available. For example, the reference to hybrid cars, which reclaim the energy gained by climbing a hill on the way down, was first made in 1894, but the technology came into existence only in 2008. Today, commercial vehicles such as the Toyota Prius use this technology [25], and the technology is considered to be very effective. Some of these predictions of science fiction literature are not just ideas, but contain technological details of how these ideas can be made into reality, for example, as in the case of producing energy from organic waste [26]. Given the state of the society at a certain period (for example in the 1940s), it is an extraordinary feat to imagine the future so accurately. There were many instances where ideas proposed by science fiction are being currently researched but still have not reached a commercial stage—for example, flying cars and vibration-propelled vehicles. Some ideas proposed hundreds of years ago seem to remain unfeasible in the near future, such as changing the axis of the earth so that the seasons are more temperate and uniform as a way to control the climate [27].

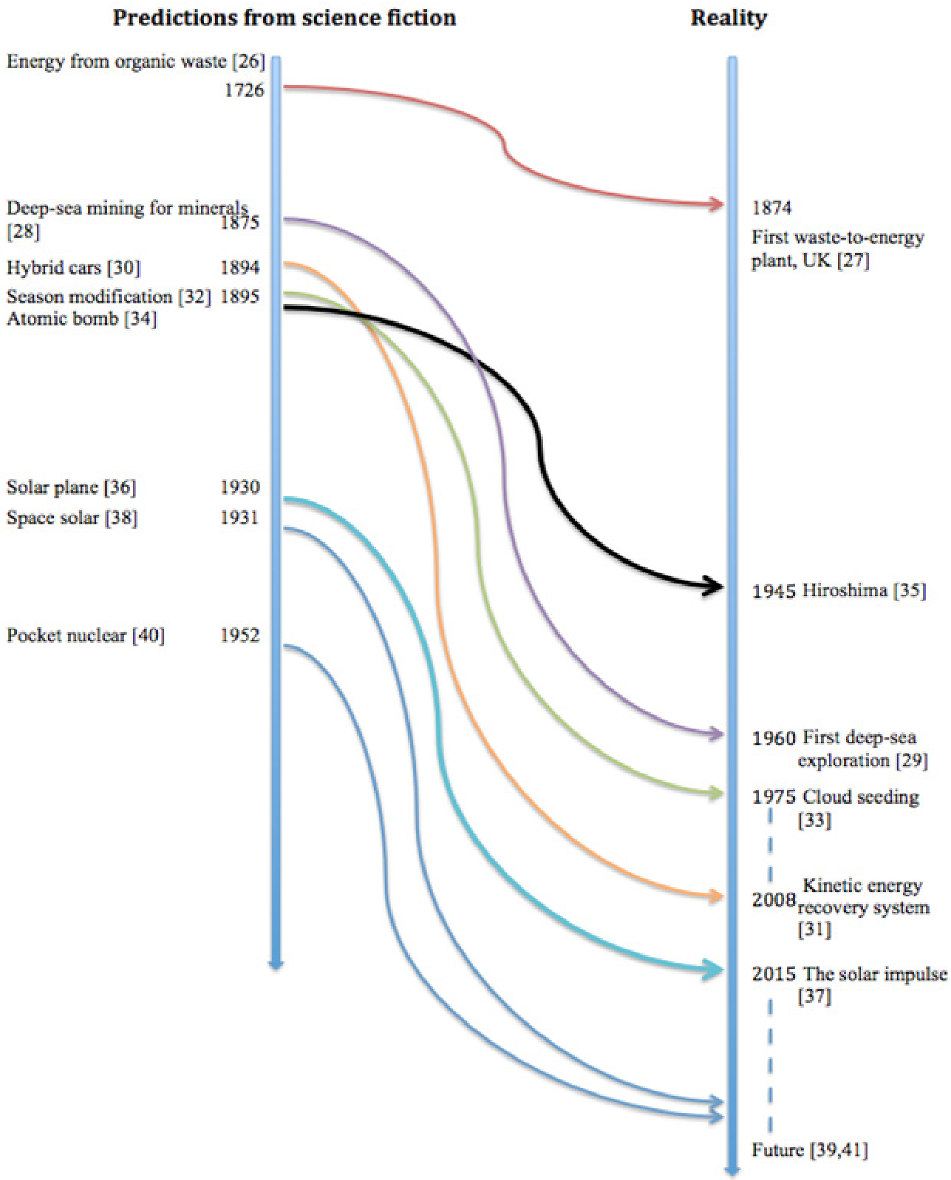

Figure 2. ***Timeline showing the first reference to a technology in science fiction literature (left) and when it became a reality (right). [26-41]***

4 Energy in Our Selected Books

In addition to collecting an overview of books, we took a deeper look into the ideas and contexts of energy in science fiction. As reading thousands of science fiction novels was not in our feasibility range, we narrowed our focus to books that represent different eras and energy solutions. An important aspect was that the considered stories are classified as "hard science fiction," meaning that they abide by the known rules of physics. We tried to select authors who are well known and also possibly have backgrounds in natural sciences. Especially Robert A. Heinlein and Isaac Asimov did much in the 1940s to bring scientific responsibility to science fiction [42]. Our selected books are from different time points in the last century, with earliest ones being from the 1940s and 1950s and including also recent publications for an up-to-date point of view. A very important selection criterion was that the story also has a description of the energy concept, as for many purposes it is easy to omit the solutions from the storyline. Our review presents a collection of ideas that can emerge from futuristic literature. We have categorized our examples under three topics: antimatter, which is the most futuristic category; energy harvesting, presenting some smaller-scale solutions; and solar power, including both space-based and terrestrial solar power, which is the closest to becoming economically viable in the large scale.

4.1 Antimatter

One of the most far-fetched energy sources in science fiction literature is antimatter. Antimatter consists of particles that have the same mass as, for example, electrons, protons, and neutrons, but their charge and various other physical qualities are the exact opposite. So, for example, an anti-electron, a positron, has the mass of an electron, but its charge is positive instead of negative. The existence of antimatter was hypothesized first around the turn of the 19th and 20th century, and its nature more concretely described by Paul Dirac in 1928 [43]. Antimatter is interesting from an energy perspective because when a particle meets its antiparticle, they both annihilate, and as a result, the full atomic energy bound in their mass is released. Thus, antimatter has a very high extractable energy density: it is roughly a thousand times higher than that of uranium and a billion times higher than that of oil. However, there are great obstacles to overcome, such as where to obtain antimatter and how to store it. Storage of antimatter is a particular problem, as it is instantly annihilated when it comes to contact with normal matter. Different magnetic, electric, and optical traps exist, but only on a demonstrative scale [44–46].

Antimatter can be found naturally or it can be produced artificially. One of the first mentions of antimatter in science fiction literature was in the Seetee series by Jack Williamson in the 1950s [47,48]. These books provided a concept of asteroid mining to produce the fictional antimatter "contraterrene" (CT, or seetee), which was described as solving all of the energy problems of the entire solar system [47]. However, finding considerable quantities of antimatter from space is quite unlikely, because of the fact that it annihilates when put into contact with regular matter. Evidence of individual positrons and antiprotons has nevertheless been observed from cosmic radiation [49]. The Seetee-series books do not fully obey the laws of physics, but in the future asteroid mining could become a source of useful and rare minerals.

Positrons, the antiparticles of electrons, are a natural by-product of beta-plus decay, a certain type of nuclear reaction. There is, in fact, one naturally occurring beta-plus decaying isotope, potassium-40, which is present in trace amounts in, for example, bananas. Unfortunately, the decay process occurs relatively rarely, which makes it an inconvenient source of antimatter. Beta-plus decaying particles can also be artificially created through irradiation, but this process typically takes more energy than the resulting positrons hold.

Interestingly, positrons have already some feasible small-scale medical and scientific applications, namely, positron emission tomography, a medical imaging technique [50], and positron annihilation spectroscopy, a semiconductor characterization technique [51]. Another way of generating antimatter is through high-energy particle collisions. The most active research institute in this line of science is CERN, which in 2011 managed to create 309 antihydrogen atoms and store some of them as long as 1,000 seconds [52]. Antimatter is thought to be the most expensive material on Earth, costing from tens of billions up to tens of trillions of dollars per gram [53].

In the imaginative world of *The Quantum Thief* by Hannu Rajaniemi, antimatter provides a powerful weapon in the form of bombs, much resembling the history of nuclear energy [54]. Unfortunately, one of the discussed real-world applications of antimatter is also related to destruction, as it has been speculated that antimatter could be used as a detonator for nuclear bombs [55]. Using antimatter instead of fissile substances could reduce the long-term contamination caused by the bombs and thus reduce collateral damage. The most clearly energy-related application of antimatter discussed in science fiction literature and in reality is its possible use as rocket or transportation fuel, as is also the case in *The Quantum Thief* [54]. This is an application that would notably benefit from the high-energy density of antimatter, as the weight of the necessary fuel taken on board could be greatly reduced. Although *The Quantum Thief* and its sequels describe a post-human world with nearly incomprehensible properties far from present-day reality, the series does provide some interesting ideas, such as the possibility to obtain developmental leaps from technological singularity [56].

4.2 Energy Harvesting

Energy harvesting, or scavenging, refers to the collection of ambient energy and its conversion into electricity, or in some cases into mechanical work. Although large-scale schemes such as solar, wind. and wave energy can be considered as subtypes of energy-harvesting process, in the context of research the term “energy harvesting” is used mainly for small-scale applications and autonomous devices. The energy forms to be harvested can roughly be divided into three categories: thermal energy (heat), kinetic energy (motion), and solar energy (light) [57]. The last category will be discussed in detail in the next section as we present examples of harvesting heat and kinetic energy, which both occurred in the fictional future schemes.

In Isaac Asimov's *Foundation and Earth* [58], the story of planet Solaria continues, where highly evolved and engineered Solarians live in isolation, and meet outsiders whose quest is to find Earth again. Situated in the distant future, the Solarians have developed a sophisticated energy-scavenging system for harvesting surrounding heat for conversion to work. According to the description, the power system can be classified as geothermal:

> *This heat conducting rod extends several kilometers downward, and there are similar rods in many convenient places throughout my estate. I know there are similar rods on other estates. These rods increase the rate at which heat leaves Solaria's lower regions for the surface and eases its conversion into work.*

At the individual level, the Solarians are able to harness the surrounding heat flows by using their transducer-lobes, which are activated by the flow of heat and then convert the heat flow into mechanical energy [58]. Interestingly, the book lacks a system for power storage, as the heat supply seems to be constant and sufficient. The amount of geothermal energy is dependent upon the properties of the fictional planet, and when the scheme is situated on Earth the energy supply seems to be quite limited, as a rough estimate of the heat flow at the surface of Earth is calculated to be only 50 mW/m^2 [59]. Also in Solaria, the sufficiency of energy is ensured with a low population density, as there are only 1,200 individuals living on the planet. Although large-scale heat scavenging on Earth is unlikely to be the solution for future energy, on hot spots like Iceland and small applications it can be useful. For example, biomedical engineers are aiming to produce medical devices and body sensors that could be powered by thermoelectric generators making use of the temperature differences in the human body [60].

Kinetic energy or, more specifically, biomechanical energy production is in the center of the book *The Windup Girl* by Paolo Bacigalupi [61]. It describes a dystopian world where people are dying of rapidly mutating diseases originating from bioterrorism. The oil age, referred to as "The Old Expansion," is a mere glimpse in the past, and although there is some coal left and biogas is produced in large scale, most of the energy comes from non-hydrocarbon sources. Mechanical movement is harnessed to power-up modern electronic devices, both in large- and small-scale application:

> *Hock Seng is already sitting at his computer. His bony leg ratches steadily at the treadle, powering the microprocessors and the glow of the 12 cm screen.*

Large-scale energy is achieved with huge, engineered animals that circulate around a spindle. Is it really efficient to convert chemical energy into electricity through animal bodies? Optimally, energy harvesting should be directed to waste energy and collecting it should leave the primary energy source unaffected [57]. It is unrealistic to design animals for power generation, but collecting energy from already occurring movement is an applicable approach. This is reflected in our analysis in Section 3, as the keyword "wearable" has been an occurring theme in recent science fiction literature, reflecting the increasing discussion on wearable electronics.

One issue of energy harvesting is the need for storage due to the discontinuity of the energy source [57]. In *The Windup Girl*, mechanical energy is stored as tension in devices called "kink-springs" [61]. They are charged repeatedly with a spindle that goes through winding cycles. Kink-springs are loaded with momentum, which is then released as useful energy. Although this is mainly a made-up technology, the real world counterpart might resemble mainsprings or torsion springs that have been used to power clockwork and small toys, or perhaps flywheels, which have been implemented in modern hybrid cars [25,59]. Although they sound simple, for some purposes mechanical springs or flywheels actually are superior to lithium batteries [59]. The amount of stored energy depends on the material used, and new discoveries in material science have aided the development of next-generation springs. Carbon nanotube yarn has recently been demonstrated to have a possible application in powering practical systems [62]. They have a higher energy density than rechargeable lithium-ion batteries. The stored mechanical energy can also be also converted into electric output power, possibly enabling the vision of Paolo Bacigalupi to come into reality. The scheme of the winding carbon nanotube yarn resembles that described for kink-springs in the book (Figure 3), except the existing technology is smaller in scale.

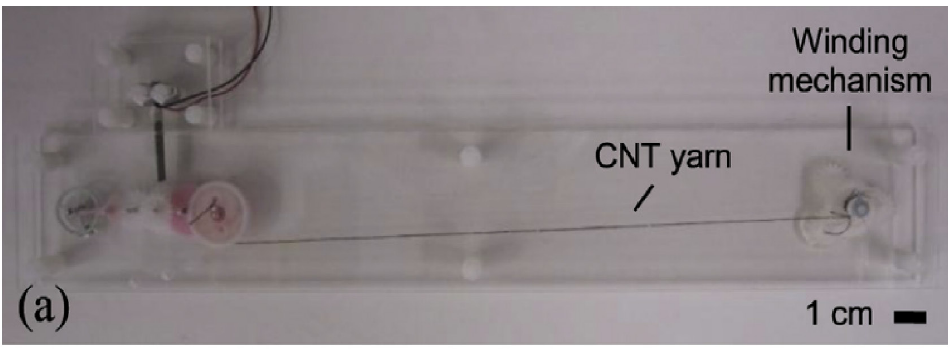

Figure 3. ***Mechanical battery based on carbon nanotube (CNT) yarn springs. With the winding mechanism the CNT yarn can be loaded with torsion, which is released and converted into electricity with a piezoelectric generator in the other end. Source: Picture adapted from [62].***

The dystopic direction of science fiction predicts an unpleasant view of the future; this might be a useful point of view because society has to come up with solutions compatible with very limited resources. Currently, energy harvesting is mainly developed for use in (small) wireless devices and sensor networks to power the Internet-of-things approach [57]. As the developed world still has relatively plentiful electricity and low-cost batteries, there is little need to implement energy-harvesting systems in common devices such as mobile phones [63]. Customer behavior probably would not support this kind of technology, at least not yet. If the price of electricity increases or availability decreases, there might be an incentive to design autonomously powered systems. However, the most common applications in this field will remain those that inherently require small fluxes of energy.

4.3 Solar Power

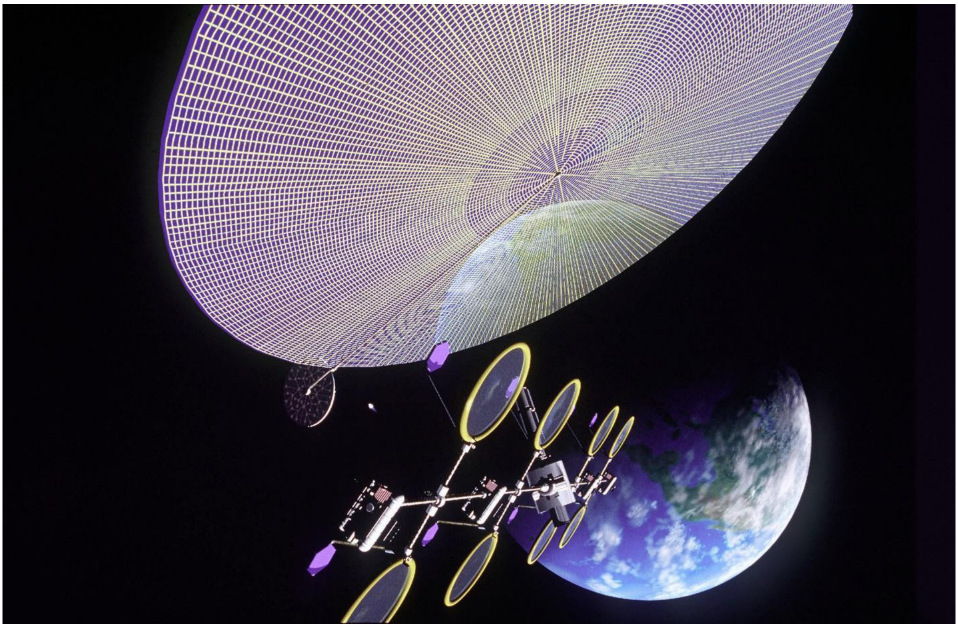

Figure 4. ***A concept figure of a solar-powered space power plant [64].***

Quite a few science fiction books have proposed the use of solar energy for different purposes in different ways (Figure 4)—for example, rooftop solar and wind (1894), sunray tank (a source for storing light) (1914), solar-powered aircraft (1930), satellites reflecting sunlight to power solar farms on the Earth (1931, 1941), and near-space solar energy collectors generating power from solar radiation closer to Mercury (1937, 1941). Even though the first commercial solar power prototypes were developed only in 1956, science fiction writers wrote about their use 15 years earlier [24]. Solar technologies in science fiction literature can be divided into two broad categories: (1) a technical innovation that dramatically decreases the price of terrestrial solar energy and (2) space-based solar power. A couple of examples of the first category include *The Man Who Sold the Moon* (1951) by Robert A. Heinlein and *Solar* (2010) by Ian McEwan [65,66]. In the first one, the breakthrough is achieved by noticing that ordinary clay exhibits an electric charge when illuminated. This allows utilizing solar energy at nearly 100% efficiency:

> *As I see it, we can design these screen to, one … take power from the sun at nearly 100 per cent efficiency; two, deliver it as cold light; or three, as heat; or four, as electrical power. We can bank 'em in series to get any required voltage; we can bank in parallel to get any required current, and the power is absolutely free, except for the installation costs.* [65]

The second book, *Solar*, presents a more complex innovation facilitating artificial photosynthesis [66]. These two examples are representative of a larger trend in science fiction literature, where the technical breakthroughs get more complex over time. This is most likely a consequence of the scientific progress present in all aspects of society. Neither of these books, or any other solar-themed books we were aware of, discusses the problems of wide-scale application of terrestrial solar energy, such as its varying output in length. Perhaps this will be tackled in science fiction literature in the near future, as these problems grow more widely known with further integration of commercial solar power.

Although these solar-related breakthroughs are somewhat naïve, they are not completely "out of this world." The creation of an electric charge under illumination, or the photovoltaic (PV) effect, was discovered by Becquerel already in 1839 [67], and later this was also observed in silicon [68]. Silicon, on the other hand, the second most abundant element in Earth's crust, serves as a fuel for visions of a silicon-photovoltaic-powered world. Additionally, silicon photovoltaics is in fact currently on the verge of wide-scale application in, for example, Germany, China, and the United States [69]. However, quite soon after the discovery of the photovoltaic effect in silicon, it was also discovered that the light-to-electricity conversion efficiency has a theoretical maximum of around 30% [70], and although silicon is rather abundant, unfortunately it covers less than one-third of the cost of photovoltaic panels today [71]. Thus, silicon photovoltaics has not yet reached cost-competitiveness with traditional power sources.

Incidentally, one way of reducing the cost of solar energy, which is currently under investigation, does indeed take advantage of artificial photosynthesis. A branch of solar cells called dye-sensitized solar cells (DSSCs) [72] is a thin-film technology currently under investigation. DSSC take advantage of the fact that illuminated organic dyes can generate electricity in electrochemical cells [73]. Currently, these cells are still tapping into expensive elements, such as titanium, and they suffer from stability problems, but wide research efforts are being undertaken to overcome these issues. It has been predicted that DSSC technology could make a major contribution to power generation as early as 2020 [74].

Unlike these two terrestrial applications, space-based solar power is still far away from commercial application. Research on space-based solar power (SBSP) began in the 1960s [75], although the concept was presented in the science fiction literature already in the 1940s, in, for example, the short story "Reason" by Isaac Asimov, which describes the interaction of a robot and a maintenance worker at a solar power station:

> *The dots to which our energy beams are directed, are nearer and much smaller. They are cold and hard and human beings like myself live upon their surfaces—many billions of them. It is from one of these worlds that Donovan and I come. Our beams feed these worlds energy drawn from one of those huge incandescent globes that happens to be near us. We call that globe the Sun and it is on the other side of the station where you can't see it.* [76]

The basic idea of the technology is to realize a power station orbiting the Earth, and then transmit the power to Earth. Most common solutions involve photovoltaic cells in the power station and a transmission system based on microwaves [77]. The main benefits of this system comprise the avoidance of the inherent intermittency of solar power and losses due to reflection and absorption in the atmosphere. If the photons emitted by the Sun would be turned into electricity and then microwaves outside the atmosphere, these microwaves could penetrate the atmosphere with a much higher efficiency. Normally, approximately 40% of photon energy is lost in the atmosphere, whereas only 10–15% would be lost in the case of microwaves [75]. Additionally, placing the orbiting power station such that it is always on the sunny side of Earth would provide continuous power through night and day.

To realize a space-based solar power station, the society needs to master six different disciplines: wireless power transmission, space transportation, construction of large structures in orbit, satellite attitude and orbit control, power generation, and power management. To make the power station a net energy producer, its size would have to be considerable, and thus the costs of the first pilot project have long been viewed as too costly. It has been estimated that before delivering the first kilowatt-hour of space-based solar power, an investment of between 300 billion and 1 trillion U.S. dollars would have to be made [78]. Despite the obvious challenges, there are a couple of interesting projects currently in development. The Japan Aerospace Exploration Agency (JAXA) has developed a technology road map leading to the implementation of commercial-scale space-powered solar power. JAXA is beginning with a 1-kW demonstration satellite in 2017, slowly building up to a 1-GW full-scale power station in 2031, with the intention of generating a vibrant space solar industry with approximately one 1-GW plant launch per year. For comparison, Japan's energy consumption rate is currently approximately 600 GW [79]. Also, China has ambitious plans for space solar [80].

5 Scenarios: Solar World in 2060

We draft four possible futures of solar power using the ideas from science fiction books, also discussed in the previous section. In our scenarios, we assume advances in solar technologies as a solution to our energy problems. Our time span is the year 2060.

Solar technologies known presently include conversion of sunlight into electricity using PV panels. These technologies either (i) are too expensive, (ii) are too inefficient for a global scale-up, (iii) require redesigning current infrastructure because of intermittency, or (iv) require too much land and sunshine, which are not available everywhere. These problems make current solar technologies unfeasible as solutions to our global energy need using just solar. Many solutions have been proposed to expand the usage of solar to a global scale, by, for example, placing solar panels in the desert regions of the Sahara to generate power for the entire world. Although this appears lucrative on paper, one of the major hindrances to this plan is the unstable political situation and lack of proper cooperation between countries.

On the other hand, as we explained in Section 4, space solar, which provides uninterrupted, abundant power, is a great advancement in solar technologies, which paves way for a future world powered by solar. The only issue with space solar is that it is either too expensive and/or requires international collaboration to be feasible.

With these two situations in mind, we identified technological development and global politics to be the two main factors that define the different possible futures of the solar power field.

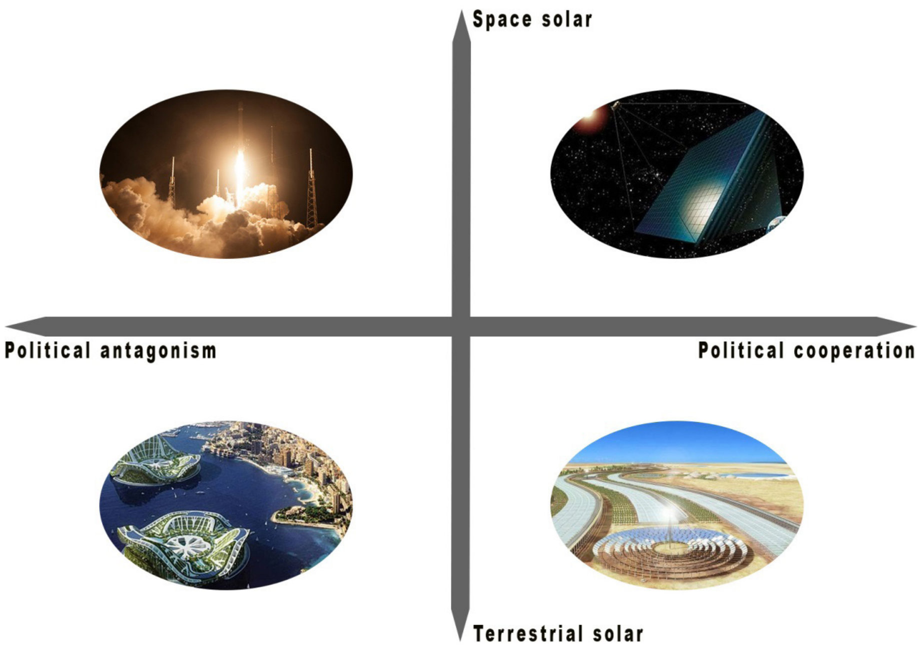

Figure 5. ***Scenario map of possible futures.***

We present four possible future scenarios for the year 2060: "New Space Race," "Space-Powered World," "Every Man for Himself," and "Global Solar Grid" (Figure 5).

5.1 Scenario 1: New Space Race (Upper Left Corner in Figure 5)

China and Japan started as forerunners in developing the technology related to space solar. China was the first to be able to actually utilize it in large-scale systems, and in the year 2021 the first Chinese collector was launched. Being able to utilize space solar was seen not only as technological victory, but such a victory also gave China a major push in the fields of international politics and was clear evidence of its power. This unexpected breakthrough caused other nations to speed up development, and a new wave of space race started in the years 2020–2040. In 2060, not only China, but also India, Japan, the United States, and South Africa were able to utilize space solar, and space solar reached a 50% penetration in the electricity mix. The European Union (EU) gave up this race a long time ago, as it had been struggling with its "earthly" problems for decades, and this new mission was beyond its economic possibilities. This space race also caused a new field of United Nations politics to emerge, space law, as there are multiple problems related to where solar space stations can have their missiles and which routes they can use to transfer the solar energy beams to earth. A couple of fatal accidents have happened. Also, challenging negotiations on which countries can utilize Mars and the Moon as their solar energy stations are ongoing.

5.2 Scenario 2: Space-Powered World (Upper Right Corner of Figure 5)

The United States, EU, Japan, China, and India have joined their forces and set up international standards for the critical disciplines required for space-based solar power: wireless power transmission, space transportation, construction of large structures in orbit, satellite attitude and orbit control, power generation, and power management. This has facilitated mass production of manufacturing and assembly robots, which are now routinely being sent to space to construct new solar power stations. Microwave power transmission is a mature technology with end-to-end efficiency of about 95%. The solar power stations map their 1-GW microwave beams on a global network of microwave receivers. The price of this electricity is determined according to demand in a global electricity market, facilitating cheap access to electricity for citizens all over the world and making the world an energy sufficient, peaceful place.

5.3 Scenario 3: Every Man for Himself (Lower Left Corner of Figure 5)

Space technology has proven too expensive, and dreams of solar stations in space have been abandoned. Germany and other Northern European countries also have deemed terrestrial solar too expensive and have abandoned governmental subsidy schemes decades ago. Solar power production has focused on areas near the Equator due to their high yearly irradiance. Key areas include the southern United States, Australia, Mexico, India, the Middle East, and large parts of Africa. In these areas, solar power comprises roughly 40% of the energy mix, whereas in other, less sunny areas, it plays a more marginal role. Due to the intermittency of solar, considerable overcapacity of solar electricity occurs during the sunniest hours of the day. The solar-power-producing countries are trying to alleviate the overcapacity by building binational transport grids, for example, from India and the United States to China and Canada.

5.4 Scenario 4: Global Solar Grid (Lower Right Corner of Figure 5)

Solar technologies have matured, with cheap PV panels being the norm. The rise of a global need for electricity and the improved political cooperation has led to a Euro-African grid, spanning across borders, providing unlimited, cheap power to more than a third of the world population across Africa and Europe. Providing for the Euro-African grid is the huge solar farm spawning 20 square kilometers in the Sahara, which transfers power to local power stations all across Europe and Africa. This has resulted in Europe and Africa being the most energy-abundant continents globally, thus dominating the world economy. Other countries are rapidly sketching similar plans, with a Pan-American electricity grid in construction and promising negotiations between India, China, Japan, and Australia to build a grid spanning the Asia-Pacific region.

6 Discussion

Science fiction can sometimes predict the future. It is the most visible and influential form of futuristic thinking in our culture [81], and although often viewed as entertainment, it can also make important scientific and societal contributions. On one hand, some science fiction stories are inspired by the most current real-life developments in science and extrapolate the consequences of those to the far or near future. On the other hand, sometimes apt guesses of future inventions can be made based on pure luck. In either way, science fiction has its role in the developments of society.

Our study has demonstrated how science fiction is already a part of future studies and how it can be utilized to project current trends and developments. The case of energy is particularly interesting, as credible scientific fiction authors need to consider how to power their future societies. Our survey of science fiction books concludes that none of the fictional future worlds relies on fossil fuels and the answer has to be found somewhere else. It is quite interesting that we found no evidence of, for example, wide-scale application of carbon-capture technologies, even though they are one of the most important components of many climate change mitigation scenarios. We also predict that themes such as energy and climate change are likely to become even more popular in the field of fiction, be it science fiction or some other genre of storytelling. Portraying the long-ranging consequences of these major problems of today is one possible way to make people act to resolve them.

One of the questions that we came across was whether science fiction might be dying. Traditional science fiction novels contain descriptions of new technological solutions, sometimes even in great detail, but we found it surprisingly hard to find physically possible ideas from literature that were not already under discussion, at least at the research level. The pace of scientific discovery has exceeded the creation of entertainment from the newest innovations. It is unlikely that science fiction will come up with technologically detailed solutions that are not yet currently under research. However, it can provide important inspiration and raise unanswered questions that innovative minds can further develop into concrete ideas. The focus of science fiction has turned from the technologies themselves to discussing the societal implications of the technologies. We think the value of science fiction is not in making detailed guesses about the future, but in inspiring and raising discussion about the course of the development.

In today's world, popularization of science is crucial to facilitate science-based political decision making and spread general scientific awareness. Science fiction plays an important role because it presents complex theories and technologies in an entertaining format. Reading science fiction induces children's interest in the natural sciences, and girls should especially be encouraged to read the genre, in order to make the gender balance in natural sciences more equal. Combining science fiction with science can be not only entertaining, but also useful in legitimizing new technological ideas and visualizing what kinds of futures they could imply. For example, MIT Technology Review releases an annual publication called *Twelve Tomorrows*, which includes short stories inspired by the real-life breakthroughs covered in the pages of the magazine. In the latest volume from 2014, technologies such as energy harvesting and fusion energy have become reality [82].

Science fiction reflects the current mood of the society. Energy-wise, the future seems dystopian, as in many stories Earth is not enough. The diminishing resources have pushed people to either travel to outer space or languish on Earth. When looking at perhaps the most crucial near-term problem of humanity, climate change mitigation, we predict that of the most popular science fiction technologies, solar power will make the most notable contribution to the world energy mix. Antimatter as a wide-scale energy production tool will most likely remain an unfulfilled promise for decades, if not centuries, although we are positive about the likelihood that new smaller-scale applications will emerge—it could be used, for example, as a rocket fuel. On the other hand, antimatter can be seen as a part of the atomic energy industry, which might play an important role in climate change mitigation already in the near future in the role of fission power or toward the end of the 21st century in the role of fusion power.

If the steady progress of kinetic and thermal energy-harvesting technologies continues, it is evident that energy harvesting will also bear many commercial applications. As the topic of wearable technologies has increased in the literature (see Figure 1), this might lead to findings of applicable small energy harvesters from fiction. Science fiction might be tapped into to find small-scale innovations and new business models, and novel technologies could even be advertised through science fiction entertainment. Companies can benefit from scanning the developments and weak signals in the environment with a wide lens, and thus avoid the typical bias in scanning activities, preference for nonfiction over fiction. In addition, we also believe that writing science fiction could be useful when, for example, technology start-ups are applying for funding, as using stories can make ideas more concrete and understandable in the eyes of people from different fields. Approachability of stories can be a benefit in probing the customer and user experience with a science fiction prototype. The science fiction prototyping and sociocultural prototyping methods introduced in Section 2.3 could be utilized by every team looking for new ideas.

7 Conclusions

Our article highlights the importance of science fiction literature in shaping the future of our society. Science fiction can be used for legitimization and popularization of new scientific ideas, and it can act as a concrete catalyst for innovative product, strategy, and scenario development. In particular, this article focuses on the issue of energy. We explore a range of energy-related applications and show that in many cases, mentions in science fiction literature predate the commercial applications of various phenomena. We find considerable parallels between literature and real-world applications in three fields of energy: antimatter, energy harvesting, and solar. This suggests that science fiction literature can act as a trendsetter also in the future. As we considered solar energy as the most feasible energy scheme of the literature, we visualized four different scenarios describing the state of solar energy in 2060. To conclude, in such an important field as energy, the power of fiction cannot be overlooked.

Acknowledgments

Thanks to DSc. Aapo Varpunen from VTT for his insights on energy harvesting and Prof. Victor Callaghan for discussion on science fiction prototyping and valuable help in this area.

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Can Greenland Be Green?

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Abstract. The Arctic and its less exploited natural resources attract international attention. It is also subject to global drivers such as climate change, increased energy demand, and population growth. Greenland, the world's biggest island, is a crucial part of the Arctic region. It suffers from a decreasing population, a high unemployment rate, and a heavily negative foreign trade balance. Greenland needs energy and new economic alternatives to survive.

In this article we discuss the potential for renewable energy in Greenland and the Arctic. We present various renewable energy production technologies, energy storage systems, and possibilities for energy transfer over long distance, and calculate the energy potential. We present alternative solutions for Greenland and small Arctic communities. We discuss the possible consequences in terms of energy, environment, and socioeconomics. We conclude with four development scenarios and identify a path for a greener future of Greenland and the Arctic.

Keywords: Arctic, Greenland, renewable energy sources, scenarios

1 *Introduction*

The Arctic region is an internationally attractive region. It will not stay untouched in the flow of global drivers such as climate change, increasing energy demand, urbanization, and population growth. The Arctic offers potential in the energy sector in the areas of fossil fuel resources, such as oil and gas; renewable energy sources, such as wind, solar, and wave; and possibilities for storing and transporting energy across the Arctic Ocean.

1.1 Greenland Today

Greenland, located between the Arctic Ocean and the North Atlantic Ocean, is the world's largest island (Figure 1). The area of Greenland totals 2.17 million km^2, but only approximately 20% of that is ice-free. The coastline is 44.087 km long. The climate can be defined as arctic with cool winters and cold summers. The mean temperature of the summer months is below 10°C.

Figure 1. ***Greenland on the map [1].***

Greenland is part of the Kingdom of Denmark, but it is not a part of the European Union (EU), as it withdrew from the EU in 1985. In 1979 Greenland was granted Home Rule, but a self-rule government was established only 30 years later, on June 21, 2009.

The population of Greenland in the beginning of 2014 was approximately 56,300, and 85% is urban. The number has decreased slightly during the past years. Half of the population is 25 to 59 years old, and about 10% is above 60 years of age. Emigration exceeds immigration by about 500 persons per year.

Greenland's economy is small and dependent on subsidies from Denmark. The Danish block grant accounted for more than 50% of government spending and 25% to 30% of Greenland's gross domestic product (GDP) in 2013 [2]. The GDP of Greenland in 2012 was 11.54 billion Danish kroner (DKK) and had decreased by 0.9% as compared to 2011. Exports counted for 2.76 billion DKK in 2012. At the same time, imports counted for 4.96 billion DKK, making the trade balance negative. Fishing is the primary industry, and fishing for prawns and Greenland halibut is regulated by the government to ensure a sustainable use of natural resources.

The public sector is the main employer; approximately 25% of the employed population works in public administration and services. Fishing, hunting, and agriculture account for 14% of total employment, wholesale 12%, transportation 11%, construction 8%, business activities 6%, and mining only 0.4%. The unemployment rate in 2012 was 12.5%.

Due to the aging of the population and other societal changes, Greenland is facing steadily increasing social welfare costs. The major parties in Greenland hope to cover the increasing costs with revenue from oil and mineral exploitation, as Denmark's annual grant was frozen to the level of 2009 due to the establishment of the self-rule government.

As the Greenland Ice Sheet continues melting, due to global warming, its mineral and energy resources are becoming more accessible. Natural resources such as zinc, lead, iron ore, coal, gold, platinum, and uranium make Greenland attractive for the mining industry. Hence the government of Greenland has made natural resource extraction a central part of its plans to become economically self-sufficient, and ultimately independent.

1.2 International Positioning

There is an increasing international focus on the Arctic. Greenland can become the focal point of resources provided by the Arctic due to the following factors [3]:

- political stability with increasing independence
- a political push to move toward a natural-resource-based economy
- numerous mineral resource projects
- the issuing of mining licenses
- the opening of Arctic shipping lanes, providing access to Asia-Pacific region

Greenland is estimated to hold approximately 3.5% of the global rare element potential and has a strong potential in 6 out of 14 critical elements, such as niobium, platinum group metals, rare earth elements, graphite, fluor, and chromium. Rare earth elements are the key to the 21st century's economy, and the global demand for these metals is likely to increase in the future as the use of high-tech, environmentally friendly products, such as hybrid cars, continues to increase. Greenland is estimated to meet at least 25% of the global demand for rare earth metals in the next 50 years [4]. Present and future challenges make it extremely important for Greenland to choose the right partners in developing the use of its resources.

1.3 Greenland and Climate Change

Climate change and global warming affect Greenland in a very visible way: the melting of the ice cap. This melting brings serious global effects, as the Greenland Ice Sheet represents 10% of the freshwater reserves on Earth. Complete melting of the ice would make the global sea level rise more than 7 meters, consequently causing flooding in coastal areas like New York. Melting will also affect sea life and fisheries, thus affecting food production. To some point, the ice thawing opens new opportunities for agriculture, fishing, mining, and oil exploration. This development could lead to self-sufficiency in food production.

1.4 Energy in Greenland

Greenland's gross energy consumption in 2014 was close to 2,532 GWh. About half of the consumed energy derives from hydropower and the other half from fossil fuel. The total energy consumption decreased from 2011 to 2012 by approximately 20%, and there was a slight drift toward hydropower [5]. With a slow, even negative population growth, Greenland itself does not need much more energy in the near future. But there is a business potential of strategic importance for Greenland: to produce, store, and sell energy to other regions.

2 *Opportunities in Renewable Energies*

In this article we discuss the potential for and impacts of the use of renewable energies in Greenland and the Arctic. This chapter presents available technologies for harnessing energy from renewable sources, such as the ocean, wind, sun, and geothermal. The background is complemented by simple calculations that illustrate the opportunities of sustainable energy production in the Arctic, with Greenland as an example.

2.1 Energy from the Ocean

Greenland is an island surrounded by ocean [5], and the sea forms the largest single potential source for renewable energy. Energy can be harnessed from, for example, tidal currents or waves, or differences in salinity [6]. None of the ocean energy technologies is widely deployed yet; however, the International Energy Agency (IEA) believes that these technologies could start to play a significant role in the global electricity mix around 2030 [7], and in Europe it is estimated that about 15% of the European electricity mix could be covered with ocean energy by 2050 [8,9]. As compared to other renewable energy sources, ocean energy is more consistently available and can respond to the base demand of electricity [8,10,11].

Ocean energy technologies also offer potential for the social and economic development of Greenland and the Arctic. Benefits include a constant and local energy supply beyond the current grid [8,11]. It is foreseen that by utilizing existing capacity and know-how from, for example, marine engineering industries, the utilization could rapidly increase and concurrently support the creation of economic growth [8,11,12]. The following subsections present various technologies for harnessing ocean energy and estimations of the renewable energy production capacity of Greenland.

2.1.1 Wave Energy

Wave energy can be defined as third-hand solar energy, the end result of wind caused by the sun. It produces power per unit length. A key indicator of wave power is wave height. The longer the distance and time a wave travels, the higher is the wave and the more energy it brings along [12,13].

Wave power technologies are divided into two main groups: *deep-water devices* and *shallow-water devices*. These can be divided further into six concepts based on wave-energy-harnessing technologies. Devices harnessing kinetic wave energy through floating and moving parts include the point absorber, the attenuator, and the oscillating wave surge converter. Two device categories use turbine technology: the floating oscillating water column and the overtopping device. The submerged pressure differential is the only device fixed to a specific location and with only partially moving parts. These concepts are shown in Figure 2. Currently, more than 170 different technologies based on these six basic concepts have been developed [12,14].

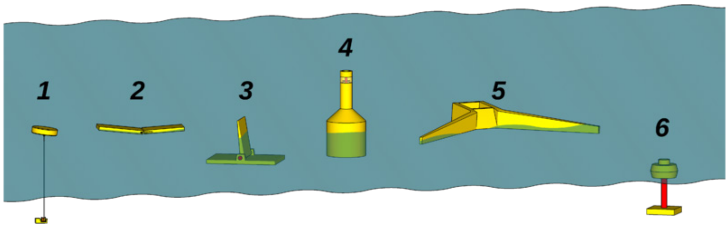

Fig. 2. ***Concepts for harnessing wave energy: (1) point absorber, (2) attenuator, (3) oscillating wave surge converter, (4) oscillating water column, (5) overtopping device, (6) submerged pressure differential [14].***

Wave technologies are not yet commercially feasible. Main barriers include low conversion efficiencies of 35% to 37% for electricity production, environmental loads caused by the devices in action, and costs. In Greenland the yearly mean wave power also varies hugely depending on the ice coverage. As shown in Table 1, roughly 21 km of wave power harnessed for energy production with an efficiency of 35% would be enough to cover the yearly gross energy consumption of Greenland. However, wave power is suitable for electricity production only.

2.1.2 Tidal Currents

Tidal currents are caused by tidal forces of the gravitational attraction between celestial objects and depend on the positions of the Moon and Sun, the effects of the Earth's rotation, the local topology of the sea floor, and the local geography. An advantage as compared to wave energy is that tides are more regular in nature [12,15].

Tidal power refers to two types of energy: (1) the potential energy associated with tides that can be harnessed by building a barrage or other forms of construction across an estuary, and (2) the kinetic energy associated with tidal (marine) currents that can be harnessed using modular systems [7]. Tidal power technologies are hence divided into two types: *tidal range technologies* and *tidal stream technologies*. The tidal range technologies refer to energy production through barrages making use of the height differences between high and low tides. Tidal stream technologies use the movement of water meeting land or underwater channels and harness the kinetic energy through, for example, generators based on power turbines [16]. Of existing ocean technologies, the tidal technologies are closest to market readiness [10,12]. An estimation of the required size of a tidal pool so as to cover the yearly gross energy consumption of Greenland is shown in Table 1. Figures 3 and 4 illustrate the tidal movements of Greenland. Greenland is among the areas on the globe with the biggest tidal power potential.

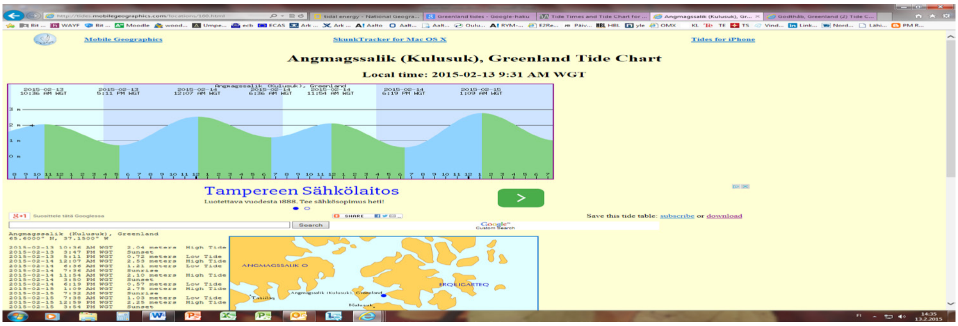

Figure 3. ***Projected tides, Angmagssalik, Greenland, February 13–15, 2015 [17].***

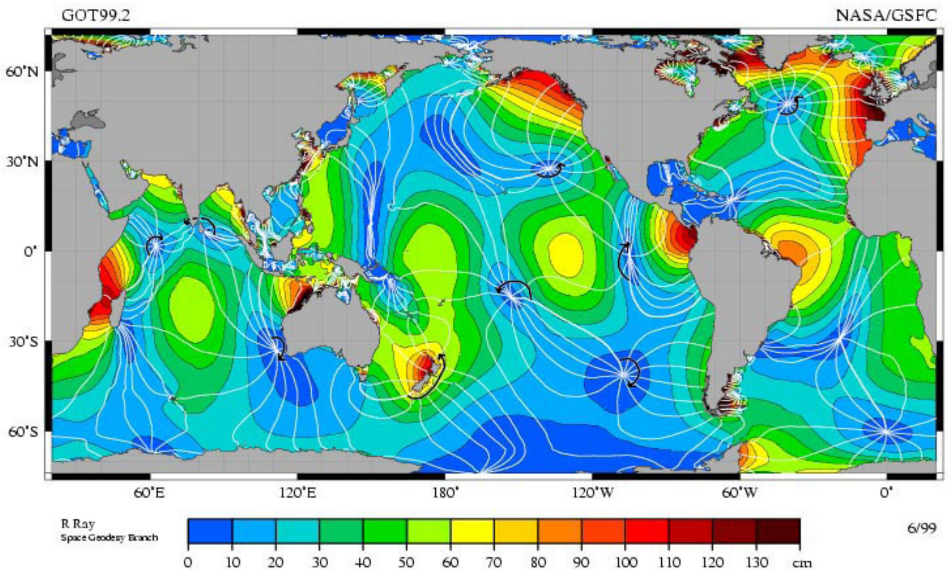

Figure 4. ***The M2 tidal constituent, 2007. The amplitude of the tidal movement is shown by color, and the curved arcs show the direction of tides. Greenland is on the top right. According to the image, southern Greenland is among the areas on the globe that experience the greatest amplitudes as well as several different 6-hour phases along the coast. In a global perspective, Greenland is among the areas with the greatest potential for tidal power, along with the western coast of Europe [18].***

Table 1. ***The gross energy consumption of Greenland in 2014 was approximately 2,532 GWh. The table shows various alternatives to cover the demand by energy from the ocean. However, the demand includes energy for heating, electricity, and transport, whereas the suggested technologies are mainly applicable for the production of electricity.***

Energy	Technology	Availability Area/ Surface/ Extent	Maximum Output	Mean Output and Efficiency, Greenland	Suggested Installed Capacity	Mean Output
Wave power	Wave energy converted to electricity	Total assumed wave energy potential, constant mean power of 40 kW/m	Current: 35% efficiency	35% efficiency, 14 kWh/meter	21 km	2572 GWh/year
			Future: 50% efficiency	50% efficiency, 20 kWh/ meter	15 km	2625 GWh/year
Tidal range		3–13W/m^2 power per unit area of tidal pools, tidal range 4–8 meters [13]		Assume average power per unit of 7 W/ m^2 and 50% extraction efficiency	45 km^2	2745 GWh/ year

2.1.3 Temperature Gradients

The temperature of the sea typically varies with the depth. This variation is caused by solar heat stored on the surface and temperatures of between 4°C and 7°C in depths below 1,000 meters. The phenomenon can be utilized for energy production through *ocean thermal energy conversion* (OTEC). The potential is dependent on differences in temperatures of 20°C or more. Hence the global potential is limited to regions close to the Equator [12]. Even with a significant climate change impact, the potential in the Arctic and Greenland will most probably remain small. Therefore this alternative is not further explored in this context. However, the constant temperature of the deeper sea layers can be utilized for heating and cooling, as discussed in the section on geothermal energy.

2.1.4 Salinity Gradients

The saltiness of seawater varies and is referred to as the salinity gradient. Two basic concepts for harnessing energy based on differences in salinity gradients have been developed: *reversed electrodialysis* (RED) and *pressure-retarded osmosis* (PRO). RED technology produces electricity based on chemical differences between different salt solutions. Mixing two salt solutions also produces heat. PRO technology is based on converting this heat into a pressure difference and further into energy. One example of a natural environment where such mixed water would occur is river mouths ending in the sea [12,16]. Due to the nature of the energy source, fresh water and saltwater, the supply is constant. The first European energy production facilities based on salinity gradients are in Norway and the Netherlands [8].

In Greenland, water of different salinity gradients can be found both along the coastline and in the sea. The ice cover in Greenland melts on a yearly basis. The runoff forms a supraglacial river network, moving large volumes of fresh water toward the sea [19]. Such a network of rivers forms a potential source for both hydropower and the utilization of salinity-gradient-based energy conversion technologies. As a result of climate change, the runoff is expected to increase.

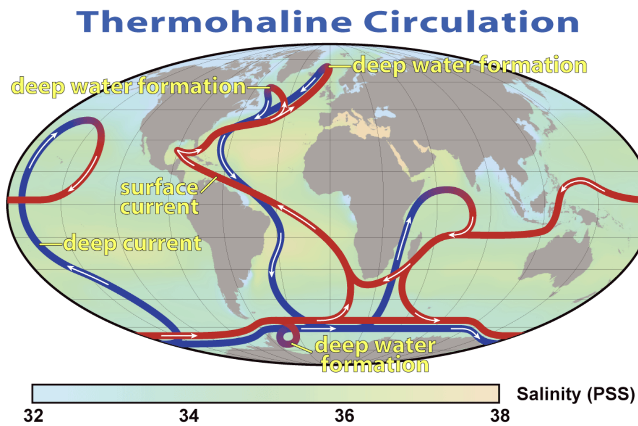

Figure 5. ***The global thermohaline circulation. Greenland is in the center of both cold, deep currents of low-salinity water and warm, salty surface flows. Source: NASA Earth Observatory [20].***

Greenland is also subject to the *thermohaline circulation* (THC) (Figure 5). The circulation is caused by density differences in seawater [21] resulting in two strong currents along the eastern coast of Greenland. The *East Greenland Current* (EGC) is a deep flow that transports cold, low-salinity water southward [21,22]. The northbound surface current of saltier water in the Greenland Sea is referred to as the *Warm North Atlantic Current*. Hence eastern Greenland and the Greenland Sea offer a constant mix of seawater of different salinity gradients [21]. Accordingly, many models imply that THC in the Atlantic could weaken as a result of climate change, but the effects of meltwater runoff and a decreased ice sheet of Greenland are unknown [21]. The exploitation of energy from salinity gradients is still on an experimental level.

2.2 Geothermal Energy

Geothermal technologies generate electricity and/or heating and cooling from renewable energy resources with very low levels of greenhouse gas (GHG) emissions. They thus play an important role in realizing targets in energy security, economic development, and mitigation of climate change. Geothermal energy can be divided into two subcategories depending on whether the resources are hydrothermal or hot rock [23].

Geothermal energy is concentrated in areas where geological conditions permit a high-temperature circulating fluid to transfer heat from within the Earth to the surface through wells that discharge without any artificial lift. The fluid in convective hydrothermal resources can be vapor- (steam) or water-dominated, with temperatures ranging from 100°C to over 300°C. High-temperature geothermal fields are most common near tectonic plate boundaries, and are often associated with volcanoes and seismic activity resulting in readily accessible heat sources [24].

Heat stored in low-porosity and/or low-permeability rocks is commonly referred to as hot rock resources. These resources are characterized by limited pore space and/or minor fractures and therefore contain insufficient water and permeability for natural exploitation. Hot rock resources can be found anywhere in the world, although they are found closer to the surface in regions with an increased presence of naturally occurring radioactive isotopes (e.g., southern Australia) or where tectonics have resulted in a favorable state of stress (e.g., the western United States) [25].

The exploration of geothermal energy in Greenland is still at an early stage. Surface manifestations of geothermal activity are rare in this large country. They are mainly found in the basaltic areas at Scoresbysund and Disko, and a single geothermal site in Uunartoc, South Greenland, is used for bathing. The Greenland Glacier covers over 80% of the country, and the majority of all hot springs and geothermal sites are believed to be ice covered. The highest temperatures are found on the east coast, north and south of Scoresbysund, and the warmest spring there is near Cape Tobin, 62°C. The warmest one in Disko is around 18°C, and in Uunartoc the temperature is 37°C [25]. Geothermal springs in Greenland are shown in Figure 6.

The possibility of geothermal utilization in Disko, West Greenland, has been investigated to some extent. Twelve small geothermal fields are known there. One of the warmest is near the town of Qeqertarsuaq. Research drilling has been suggested but no action has been taken because of nature conservation efforts. Limited information about the geothermal gradient and heat flow in Greenland has been reported. Currently, geothermal water is used in natural spas in one or two places for bathing, balneology, and tourism, with little economic return.

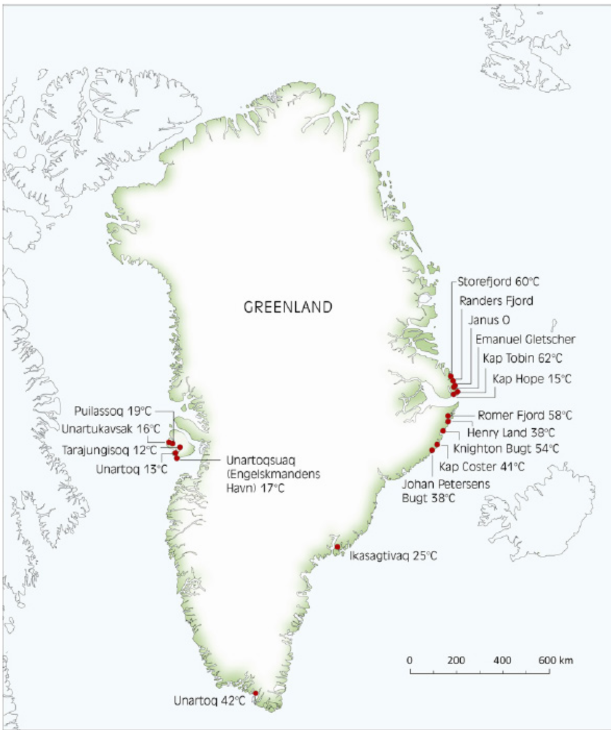

Figure 6. ***Geothermal springs in Greenland ≥ 10°C [23].***

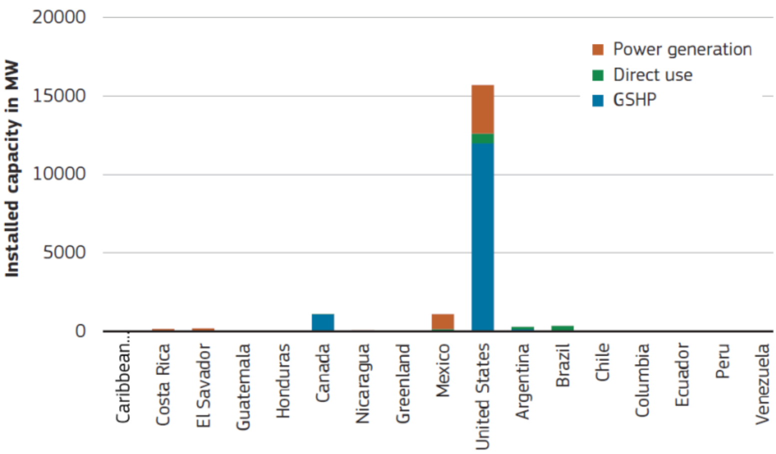

Figure 7. ***Installed capacity for geothermal energy use in the United States [24].***

As shown in Figure 7, geothermal energy is not yet used in Greenland. Geothermal energy with homeothermic source water temperature greater than 2°C (homeothermic springs) can be found all over Greenland, but very hot and warm springs (> 10°C) are very rare. Thus, electricity generation from geothermal sources in Greenland is unrealistic. However, it can be used for heating. Table 2 presents an approximate electricity generation estimate for the Scoresbysund area. This calculation is based on the current exploratory progress in Australia. The values of parameters and variables are based primarily on research from the Scoresbysund area, which is the warmest spring in Greenland. In this calculation, we followed the procedure that is described by Broliden and Hellstadius [26].

Table 2. ***Parameters and generated electricity for Scoresbysund area.***

Parameters	Base Case
Number of production wells	9
Production-injection well ratio	0.3
Depth of wells (m)	4,000
Casing strings	4
Capacity factor (%)	90
Flow of geothermal fluid (kg/s)	18
Temperature of incoming geothermal fluid (˚C)	62
Temperature of rejected geothermal fluid (˚C)	12
Distance of grid (m)	0
Available thermal power (MW)	0.01434
Net generated electric power (MW)	.001
Annual produced electricity (MWh/year)	8.76

2.3 Wind Energy

Wind is used as a renewable source of energy for electricity production by capturing the kinetic energy of the air flow with turbines. Wind farms can be built onshore or offshore. Although the offshore wind has higher power and less visual pollution, the difficulties of construction and maintenance, which might make the facility 50% more expensive than a comparable onshore one [27], as well as the challenges related to the transmission of energy from offshore locations to the populated consumption areas are still costly and challenging. A cost component comparison of onshore and offshore wind energy projects is shown in Figure 8.

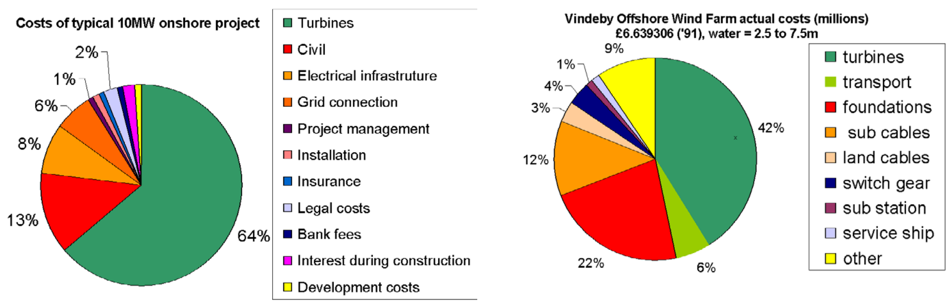

Figure 8. ***A cost component comparison of onshore and offshore wind energy projects [27].***

An estimate by Archer and Jacobson sets the total potential of the wind energy on Earth at approximately 72 TW for the year 2000, which is far higher than the world´s annual energy consumption [28]. Total global onshore wind energy potential is shown in Figure 9. Figure 10 shows the offshore annual wind map. Greenland is among the regions with high potential for offshore wind, especially in the southern parts with ice-free waters.

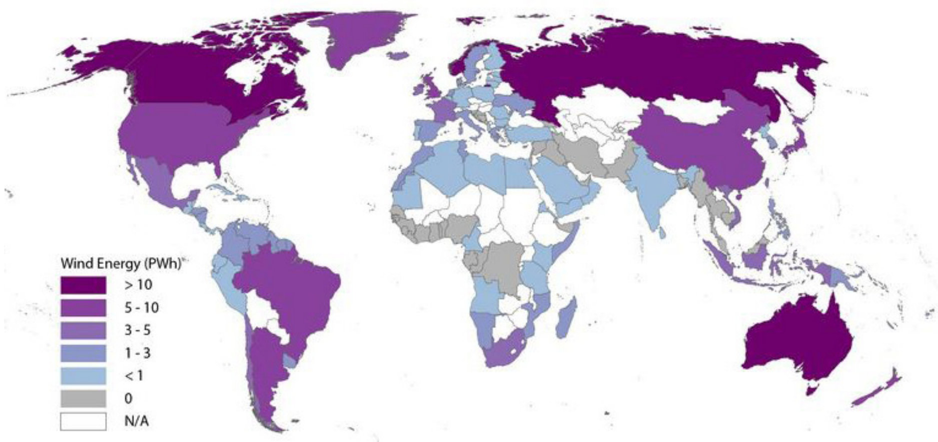

Figure 9. ***Global wind energy potential [27].***

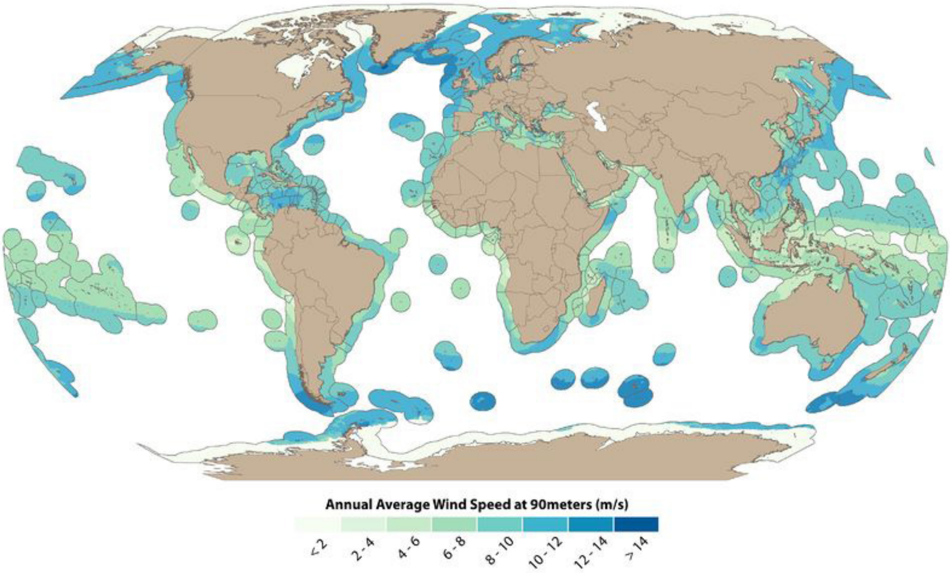

Figure 10. ***Offshore annual wind map [29].***

According to the National Renewable Energy Laboratory (NREL), Greenland had an estimated area of 151,028 km^2 suitable for onshore wind farms [29]. Currently Greenland does not utilize the wind-generated electricity. Global mean wind speeds are shown in Figure 11.

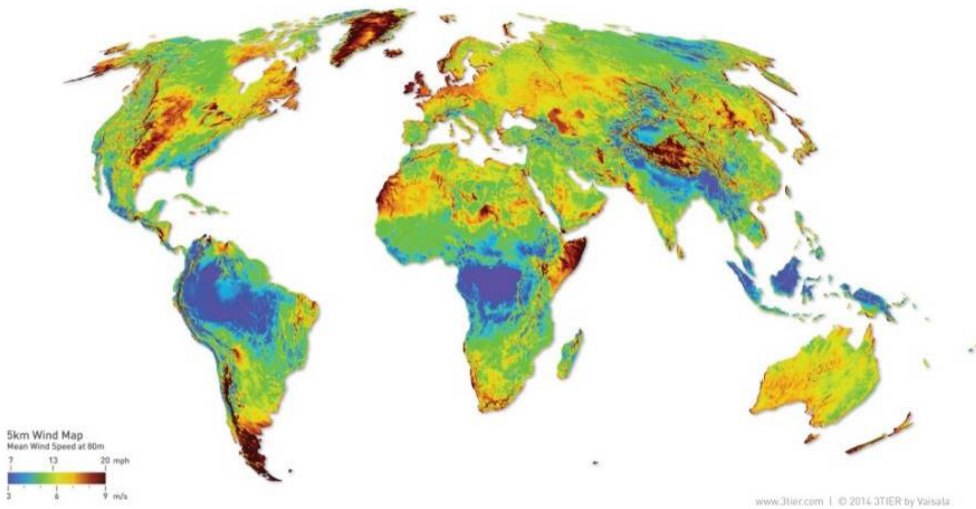

Fig. 11. ***Global mean wind speeds [31].***

To estimate Greenland's electricity generation potential from wind, we calculate onshore and offshore capacities. The reference for the offshore estimation is the Gemini Offshore Wind Farm. Assuming that one-sixth of Greenland's coastline can be used for wind farm projects, we end up with approximately 7,300 km. Offshore windfarms are usually far from the coastline; therefore we assume an area of 7,300 by 10 km, for a total of 73,000 km^2 area 60 km away from the shoreline. The Gemini wind farm has a capacity of 38 GWh per square kilometer per year [32]. Hence, the Greenland capacity totals 2.77 PWh of yearly offshore wind electricity potential.

Assuming one-fifth of the ice-free land can be dedicated for wind power generation, the onshore capacity of Greenland is about 82,000 km^2 multiplied by 13 GWh per square km per year (utilizing the Biglow wind farm data [33]), resulting in approximately 1.06 PWh. Hence, even without a possible melting of the Greenland Ice Sheet, the total capacity of wind energy production is about 3.85 PWh.

2.4 Solar Energy

According to Ramachandra and Shruthi [34], the Earth annually receives 1.5×10^{18} kWh of energy from the Sun, which is 10,000 times larger than the global energy consumption. Solar energy can be converted to electricity; however, there are several factors affecting the amount that can be converted. For example, the angle of emission, which is different in distinct geographical locations and times of day, as well as weather influence the amount of energy transmitted through sunlight [13]. Therefore, among the main challenges of this source of energy is the need for storage, as levels fluctuates throughout the year, for example, summer versus winter, as well as during the day (nighttime and cloud cover). To solve this problem a robust infrastructure, such as smart grids, and alternative sources of power can be utilized.

Two common methods for harnessing solar energy are photovoltaic (PV) cells and concentrated solar power (CSP). The first method converts the energy of the light photons directly to electricity, whereas the second method converts the energy to heat and utilizes steam turbines to produce electricity [35].

With regard to Greenland's geographical location and significant fluctuations in daylight throughout the year, the solar power per square meter of ice-free land (410,449 km^2) might be lower than the average number of 100 W/m^2 for England [13] at approximately 40 W/m^2. Therefore, if we assume one-fourth of the ice-free land can be dedicated to solar farms and the efficiency of the solar cells is approximately 30%, the annual power generation capability of Greenland from solar energy will be about 5 PWh per year if an average of 10 hours of sunlight per day can be harvested throughout the year. Figure 12 illustrates the global mean solar irradiance.

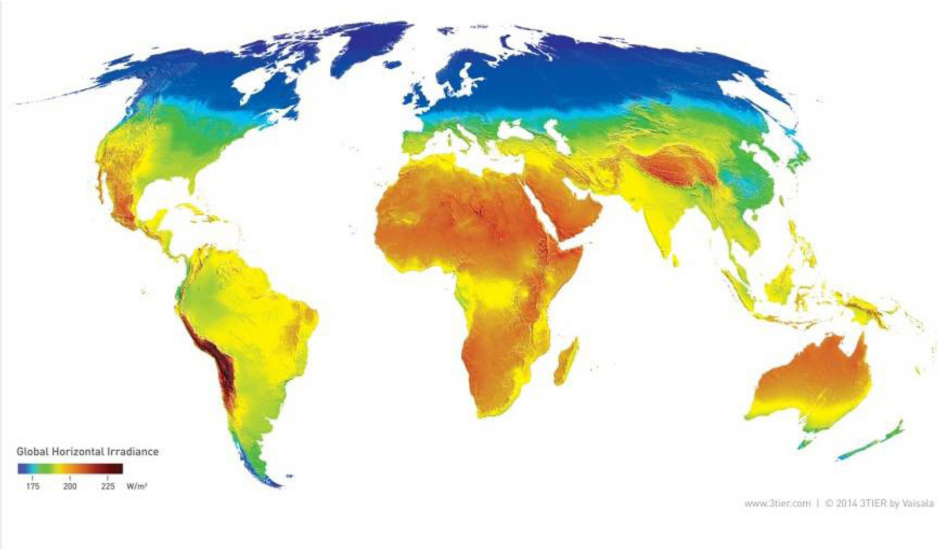

Fig. 12. ***Mean solar irradiance [30].***

2.5 Renewable Energy as a Resource

As presented in previous sections, Greenland possesses great opportunities in renewable energies, especially energy from the ocean and wind. Hydropower is currently most used. Solar power is feasible in certain locations and in certain times of the year, and geothermal has potential for heating purposes.

The yearly gross energy consumption can be covered with most of the technologies, and the maximum potential by far exceeds the local demand. For example, available and extractable wind power in Greenland totals 3.85 PWh. Main barriers for the exploitation include investments costs, the lack of mature technologies, and the need for feasible solutions for storing energy. Greenland could be a net provider of energy to other countries provided that long-distance transit of energy could be solved. The following sections presents alternative energy storage solutions for a greener Greenland.

3 A Prerequisite: Energy Storage Technologies

The world's power generation trend is slowly but surely moving toward renewable and sustainable energy production schemes. With renewable sources, one key obstacle is the dynamic nature of the production from sources such as wind and solar. There are times when the availability of the renewable sources is too high and the electricity production exceeds the demand. For example, in Germany such an event occurred on August 16, 2014 [36]. Due to the high availability of solar energy and the rapid production rate, the electricity price dropped to negative. In such cases the operators choose to pay the electricity users to consume electricity in order to avoid the shutdown of their plants, which is a costly operation in itself [37]. In contrast, there are days when the supply from renewables may be very low.

Because of the stochastic nature of renewable sources, energy storage systems (ESSs) promise to play a crucial role in enhancing the flexibility and controllability of the electricity production system in a sustainable manner. In this section we introduce the available ESS technologies presented in literature and implemented in different places. We also discuss the definitive parameters that influence these technologies and affect their implementations.

3.1 Energy Storage Technologies

As presented in Pickard, Shen, and Hansing [38], electrical energy can be converted to the following forms for storage and later usage:

- Gravitational potential energy with water reservoirs
- Compressed gas or air
- Electrochemical energy in batteries
- Chemical energy in fuel cells
- Kinetic energy in flywheels
- Magnetic field in inductors
- Electric field in capacitors

We discuss these technologies in more detail in the following subsections.

3.2 Pumped Hydro Storage (PHS)

Pumped hydro storage (PHS) technology stores electricity as gravitational potential energy. Water is pumped from a lower water reservoir to a higher location during high production and low demand of electricity, and repoured in the opposite direction, reproducing the electricity by activating a turbine, when the demand is high and/or the production is low. Energy stored is proportional to the size of the reservoirs and the distance from which water falls on the turbines. A PHS installation generally lasts 30 to 50 years, the efficiency rate of regenerating electricity is around 65% to75%, the response time is less than 1 second, and the power cost is around 500–1,500 euro/kW and 10–20 euro/kWh [39].

3.3 Compressed-Air Energy Storage (CAES)

In compressed-air energy storage (CAES), energy is stored as compressed air in underground reservoirs at the time of excess production. To use the energy, the compressed air is heated up and an expansion procedure follows. Through a combination of high- and low-pressure turbines, compressed air is converted into kinetic energy.

A few CAES systems are already in operation: a 290-MW plant in Germany and a 110-MW plant in the United States [39]. The CAES system has the advantage of very low self-discharge and is thus considered a good option for long-term energy storage. The expected lifetime of such storage systems is 40 years, with an efficiency of about 70% [39].

3.4 Battery Energy Storage Systems (BESSs)

Battery energy storage systems (BESSs) technology is perhaps the oldest and most widely deployed energy storage system to date. This technology is rather mature, and there are various types of batteries. In a BESS, energy is stored in the form of electrochemical energy in a set of cells. Common BESS technologies and their characteristics are as follows:

- Lead-acid battery: Technologically mature; low self-discharge; suitable for long-time energy storage; poor performance at low and high temperatures; needs periodic water maintenance
- Nickel-cadmium battery: Long cycle life; low maintenance requirement; health risk hazards for humans; 10 times more costly than lead-acid batteries
- Sodium-sulphur battery: No self-discharge; low maintenance; high energy density and energy efficiency
- Lithium-ion battery: Widely used in small applications; high energy density; high daily self-discharge; not an option for large-scale applications; operating environment needs quite a few protective measures

3.5 Flow Battery Energy Storage Systems (FBESSs)

Flow battery energy storage systems (FBESSs) are a relatively new technology. This technology is based on the principle of reversible electrochemical reactions. Thus the operating methodologies are significantly different from those of conventional batteries. Advantages of FBESSs include a scalable energy capacity, lower installation costs for larger systems, non-negligible operating costs, very low self-discharge, a long lifetime and low maintenance, and suitability for long-term storage of energy [39].

3.6 Hydrogen-Based Energy Storage Systems (HESSs)

The hydrogen-based energy storage system (HESS) is one of the most promising alternatives to conventional energy carriers and a strong candidate for future large-scale energy storage, mainly due to its high energy density and high conversion efficiency from chemical to electrical energy [40]. In addition, HESS is now extensively researched for transportation and storage applications; companies have already deployed HESS-based vehicle filling stations, and the results are very promising [41]. Advantages of

HESSs include modular construction and installation, scalability to a wide range of sizes and power outputs, and, most important, environmentally friendly operating principles. Although the cost seems high and the efficiency initially seems low, case studies suggest that the scenario is improving rapidly and that HESSs can play a significant role in the future [42].

In HESS excess electricity is fed into an electrolyzer that converts water to hydrogen. The hydrogen is then compressed and stored in a storage unit, as in fuel cells, combustion engines, or hydrogen gas turbines. During peak hours of demand, electricity is supplied by utilizing the stored hydrogen. Advanced alkaline and proton exchange membrane (PEM) electrolyzers are the most common and effective electrolyzers used [40]. Hydrogen can be stored in its gaseous form at 200 bar and temperatures ranging between 50 and 60°C. According to the specifications, fuel cells can be the most promising application for energy storage. The technology can leverage the benefits of HESSs, such as high efficiency at partial and full load, low emissions, fuel flexibility, and quiet operation. The main challenge of HESSs is the competition with conventional gas turbines with similar efficiency and investment costs of 600–800 €/kW. Additionally, the use of hydrogen gas turbines requires some modifications in the design of conventional gas turbines.

3.7 Energy Storage with Hydrogen and Fuel Cells in Greenland

As presented previously, we claim that Greenland can be a significant resource for renewable energy that not only can serve its own needs but also act as a source for economic growth. Companies have already started implementing pilot projects for energy storage in Greenland, with an acceptable success ratio. The H_2 KT project developed by H2 Logic A/S [41] and NUKISSIORFIIT.GL demonstrates the use of hydrogen fuel cells for storing energy in Greenland [43]. The experimental plant is established in Nuuk, where electricity is used to produce hydrogen (H_2) and stored for later use in fuel cells. Waste heat is used for local heating purposes. Produced H_2 can also be transported to other locations and cities for local energy production. There is a plan to expand the project that includes hydrogen filling stations, enabling the use of hydrogen as fuel. H2 Logic has already successfully installed H_2-based filling stations in Denmark and Germany [41]. The specifications of the Greenland plant are shown in Table 3.

Given the promising future of HESS and the initial implementations, we emphasize the use of HESS. In the following discussion we present simple calculations of the requirements of hydrogen-based fuels for covering the fuel needs of all transportation in Greenland. The amount and types of vehicles in Greenland are shown in Table 4.

Table 3. ***Specifications for the Greenland H2 Logic plant [43].***

PLANT SPECIFICATIONS	
Hydrogen production type	Alkaline water electrolysis
Production capacity	19,4 Nm^3/hour (max.)
Hydrogen storage capacity	185 Nm^3 at 12 bar
Energy storage capacity	12 hours power production
Fuel cell power effect	20 kW
Grid supply	400VAC 3 phase
Compressor capacity	12 Nm^3/hour
Compressor pressure	240 bar (up to 450 bar)
Heat utilisation	From electrolysis & fuel cell
Control and surveillance	Remote operable SRO-system

Table 4. ***According to recent statistics from 2014 [5], Greenland has the following amounts and types of motor vehicles.***

Types of Vehicles	2009	2010	2011	2012	2013
Motor vehicles, total	5,009	5,855	5,386	5,929	5,857
Passenger cars	3,221	3,842	3,621	3,941	3,931
Taxis	140	214	177	243	205
Buses	68	83	83	89	83
Fire engines	104	112	122	134	145
Commercial vehicles	1,398	1,503	1,264	1,391	1,358

We project the production and consumption numbers here based on the analysis performed on hydrogen fueling stations in Honolulu, Hawaii [42].

The total number of cars in Greenland in 2013 was 4,136 (3,931 + 205), and the total number of buses was 83. One hundred kilograms of hydrogen per day is enough to fuel 25 to 50 cars, and buses consume between 25 and 35 kg of hydrogen per day. Conservative estimates suggest a daily consumption of 4 kg of hydrogen per car and 35 kg of hydrogen per bus, whereas non-conservative estimates suggest a daily consumption of 2 kg of hydrogen per car and 25 kg of hydrogen per bus.

A roof-mounted photovoltaic solar field that produces 700 kW of power per day can sustain an electrolyzer that is capable of producing 65 kg of hydrogen per day. Conservative estimates suggest that Greenland would need (4 × 4,136) + (35 × 83) kg = 19,449 kg of hydrogen per day, and that would require about (700 × 19,449) / 65 ~ .21 MW of electricity per day from similar installations. Non-conservative estimates suggest that Greenland would need (2 × 4,136) + (25 × 83) kg = 10,347 kg of hydrogen per day, and that would require about (700 × 10,347) / 65 ~ .11 MW of electricity per day from similar installations.

Hence, according to the data and statistics of the year 2013, 0.11–0.21 MW of electricity is enough to fuel all the cars and buses in Greenland using HESS technology.

4 Greenland 2050

4.1 Energy and Economy

In Greenland today, about half of the consumed energy derives from hydropower and the other half from fossil fuels. Hydropower is seen as the biggest energy reservoir. The estimated gross potential totals 800,000 GWh per year, and the potential of the 15 most probable hydropower station locations 13,00 GWh [44]. Such plants could serve both consumers and energy-intensive industry applications. However, the main barrier and reason for the high consumption of fossil fuels in Greenland today is the island-like distribution of the population into small communities. This problem is common in the whole Arctic area; 80% of the area (Russia excluded) is dominated by communities having less than 1,000 inhabitants [45]. The sparse population makes an energy infrastructure economically unfeasible. In this article we suggest to use renewable energy sources for reliable and constant energy production independent from fossil fuels. We suggest offshore solar, wave, and wind technologies, possibly supported by tidal power stations, for small-scale and local energy production.

For example, the current yearly gross energy consumption in Greenland is close to 2,532 GWh, and in January 2014 Greenland had approximately 56,282 inhabitants [5]. Hence the yearly gross energy consumption per capita is close to 45 MWh, and per every 1,000 inhabitants 45 GWh. This requires a 5-MW mean capacity equal to, for example, seventeen 300-kW Pelamis extracting electricity from waves. Another example is wind. The capacity of a typical wind turbine is exactly 5 MW. In an optimal location one turbine would suffice. However, wind and wave energy are dependent on each other and should be added to with some other renewable energy source. Geothermal energy is useful for heating, and electricity could be additionally produced directly from solar power. This concept is applicable throughout the Arctic.

As discussed earlier, the Greenland and Arctic economies are small. Three types of economies prevail: the international resource economy, the transfer economy, and the traditional economy [46]. The *traditional economy* relies on harvesting for personal consumption and living on local resources. A typical local resource is fish. This economy has suffered since the 1980s, resulting in poverty and a decreased population. Increased local electricity production from renewable energy sources would decrease dependency on fuel and provide these communities with new opportunities. For example, local food production could be promoted by using geothermal heat in greenhouses.

The *international resource economy* depends on the exploitation of local natural resources such as petroleum and natural gas, and it is a main source of monetary income for the Arctic. Where there is an abundance of hydropower, for example, renewable energies have potential for improving the environmental footprint of this industry. From a global perspective, such Arctic production could be the most sustainable option. However, industry is concentrated to certain regions due to the reliance on infrastructure and transport. Currently transport requires fossil fuels but hydrogen-based fuel cell electric vehicles (FCEVs) are being extensively researched, with some successful installations of fuel stations already. These systems are also promising for the transportation of energy. Hence sustainable energy could be a future export product: Long-distance energy transport with submarine cables is an emergent technology, and Greenland could be a desired hub to store and transport energy between Europe and North America.

The third type of economy, the *transfer economy,* relies on the public sector and can locally account for up to half of all economic activities. Supported by an abundance of energy from renewable sources, the population decrease might turn into growth, decreasing the dependency of public funding.

4.2 The Impacts of Climate Change

Climate change is an Arctic challenge. The Arctic sea ice keeps melting, and temperatures get milder. For Greenland we see various scenarios emerging. Success in tackling climate change could minimize effects on Greenland, leaving it close to status quo regarding climatic conditions even by 2100. A worst-case scenario would be the complete melting of the Greenland Ice Sheet, with unpredictable consequences (e.g., sea currents). A rising global temperature could also result in the human population emigrating further toward the poles, exploiting new territory and resources. A moderate scenario would require some success in world politics and policy development, and would still include the melting of increasing areas of the Arctic sea ice but affect Greenland less severely. An unpredictable scenario would entail a natural disruption. Table 5 presents these four scenarios, here called the Sons of Greenland, From Oil to Renewables, an Abundance of Opportunities, and Nature's Revenge.

Table 5. ***Probable, possible, preferred, and unwanted futures for Greenland by 2050.***

FROM OIL TO RENEWABLES	SONS OF GREENLAND
Moderate success in international policies Climate change continues but slows down The viability of renewable energy technologies increases Arctic sea ice may partially melt but the Greenland Ice Sheet remains intact	International failure Climate change continues and even increases Resource exploitation increases Arctic sea ice and the Greenland Ice Sheet melt Based on current knowledge, a possible catastrophe scenario
ABUNDANCE OF OPPORTUNITIES	NATURE'S REVENGE
International consensus is reached and sustainability becomes the main global agenda Renewable technologies take a quantum leap in energy and economic efficiency The Arctic is preserved	Natural disruption, e.g., a volcanic eruption in Iceland, changing the world climate Unpredictable outcome

4.3 Discussion

The suggested solution of locally independent small communities would support a positive development. As discussed earlier, the gross energy consumption in Greenland and other Arctic regions could be covered by the means of any of the presented technologies (in an optimal location) or by a combination of various alternatives. We can even see a possibility to produce several times more energy by combining various renewable energy sources in single plants or locally, for example, from hydropower. However, in Nordic buildings, space heating is one of the biggest energy consumers. In this aspect the opportunities in the Arctic region vary. Unlike in Iceland, in Greenland hot springs are very rare. Thus, the potential for electricity generation from geothermal is small. However, for space heating the potential of geothermal in Greenland is significant.

Energy storage technology is one barrier for an increased utilization and export of energy from renewable sources. However, emerging energy storage system technologies present an opportunity to increase the flexibility and resiliency of sustainable energy supply systems while potentially reducing overall energy costs due to system integration and better utilization of renewables. Hydrogen energy storage systems, for example, offer opportunities to store energy at large scale, in the range of 1 GWh to 1 TWh. As a comparison, batteries typically store from 10 kWh to 10 MWh, and compressed air storage and pumped hydro are able to store between 10 MWh and 10 GWh.

Greenland and the Arctic could be green. In case of human failure or a natural disruption, both the Arctic sea ice and the Greenland Ice Sheet might melt and thus drastically change the global future. However, the Arctic could also have a sustainable future ahead. An increased implementation of renewable energy technologies would support environmentally friendly energy production and industries, the local traditional economy, and a socially acceptable development. Greenland could be a model green location.

5 Summary and Conclusions

As discussed in the introduction, Greenland attracted our attention mainly because of its international positioning, its abundance of rare earth elements, its opportunities regarding climate change, the negative impacts of unemployment and trade balance, and, above all, the potential of renewable energy sources.

We have discussed energy production capabilities in Greenland with respect to energy from the ocean, geothermal, wind, and solar. The energy production potential of renewable energy sources presented in this text is illustrated by calculations using state-of-the-art technologies. In addition, we have highlighted some potential energy storage systems.

Using wave power as a source for electricity production, an installation of roughly 21 km would cover the current gross energy demand of Greenland. With a total coastline of 44,087 km, of which approximately 25% is ice-free, the potential is virtually limitless. With geothermal, we have shown that it is possible to produce 8.76 MWh/year of electricity from Greenland, using the current exploratory progress in the same discipline in Australia, although geothermal might be more useful for the production of heating energy. The total potential for electricity production based on solar power is 5 PWh/year, and the total capacity of wind energy production is about 3.85 PWh. Hydropower is currently seen as the biggest energy reservoir in Greenland, and the gross potential totals 800,000 GWh per year.

The numbers are promising. Utilized in a proper manner, renewable energy can have a significant impact on the current challenges in economic issues, population growth, and trade balance in Greenland. Just to ignite the possibilities of smart use of such excess energy, we have also shown that 0.11–0.21 MW of electricity is enough to fuel all cars and buses in Greenland using HESS technology. One challenge that we have not addressed in the scope of this text is the transmission capabilities of such amounts of energy within and outside of Greenland. Because transmission capabilities increase with emerging new technologies, it will be interesting to see what new opportunities energy transportation can offer in such a scenario.

With Greenland's impressive potential in renewable energy production, it is possible to eradicate the current socioeconomic problems, and Greenland can be a driving force in creating new energy-intensive businesses, sustainable food production, and even export of energy to other regions of the world. We can clearly see that diverging from fossil fuels in Greenland not only reduces the environmental impact and carbon footprint, but also opens new doors of opportunities. In a stable political situation, the model can be replicated to larger regions such as the Arctic. With all possibilities harnessed, Greenland could be a model for a greener globe.

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Energy Abundance: Curse or Blessing?

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Abstract. Abundance of scarce resources is always an exciting prospect and if that resource is Energy, it can't get better. In this study, we attempt to visualize future scenario, year 2065, when the energy abundance will be a daily life reality. We look into the road to such abundance through the lens of framework that characterizes impact of energy abundance. We believe best case scenario will be driven by fission technology. Such future will also be accompanied by high level of automation, robotics, advanced transportations, and post scarcity economies based on resources abundance. However, the major challenge will be managing heat emitted from extensive use of energy.

Keywords: Energy abundance, abundance implications.

1 *Introduction*

"Free energy will promulgate a forward leap in human progress akin to the discovery of fire. It will bring the dawn of an entirely new civilization—one based on freedom and abundance." —Sterling D. Allan (Feb. 2003)

Among various natural resources, energy has been integral to human society. The availability of usable energy has had both accelerating and hindering effects in growth and development of economies. On one hand, energy has been fueling growth and development to transform societies into modern, wealthy economies. On the other hand, limited supplies have been slowing the pace of growth and development for the least developing nations. Energy consumption per capita has a strong positive correlation with human development indices (Figure 1), and especially with economic indices (such as gross domestic product [GDP] per capita). Increasing electricity consumption per capita can directly stimulate faster economic growth and indirectly achieve enhanced social development [1].

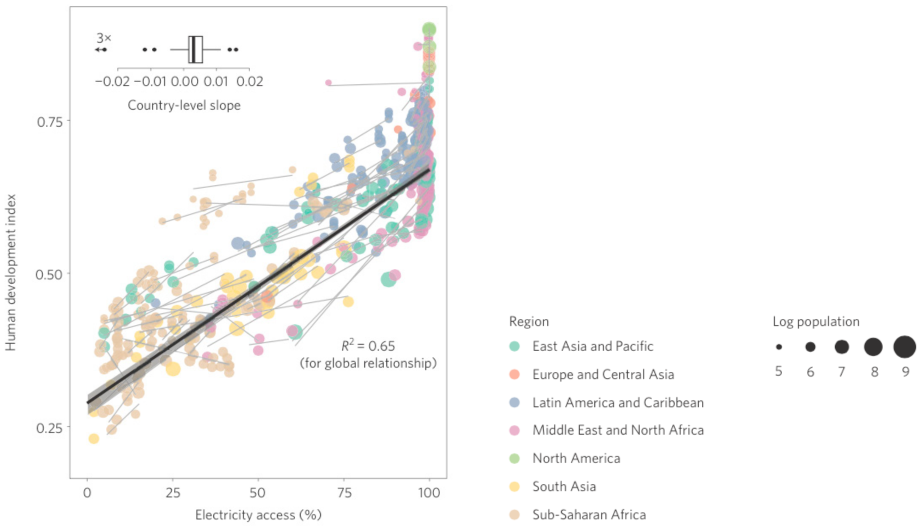

Figure 1. ***Relationship between electricity access and human development index in different populations [1].***

The world has been striving toward uncovering abundant energy supplies. Substantial investment in developing and improving the efficiency of renewable energy technology and diligent explorations to unearth more fossil fuels are significant steps toward achieving abundant energy supplies. Further, there has been continuous emphasis on energy efficiency in terms of energy production technology, energy-efficient product design, and smart energy consumption. All of these steps point toward a future world that will be blessed with abundant energy supplies. Further, a positive relationship between energy and development sets a sound foundation for the belief that a future world with abundant energy will be lit up by explosive growth and development.

The future of a world with energy abundance and subsequent technological advancement makes an interesting case to ponder. Will the impact of such a leap be positive or negative? Before getting much deeper into implications of energy abundance, we start by conceptualizing the abundance of energy and briefly examining how we achieve this abundance.

1.1 Energy Abundance

Imagine what the world might be like if we could produce energy cleanly, inexpensively, and on a global scale. What if ultra-efficient solar arrays cost no more to make than cardboard? Now add ultra-efficient vehicles, lighting, and the entire infrastructure of an industrial civilization, all made at low cost and delivered and operated with a zero carbon footprint. Then the global prospect would be not scarcity, but unprecedented abundance—radical, transformative, and sustainable abundance. We would be able to produce much more of what people want and at a radically lower cost—both economic and environmental. This isn't the future most people expect [2].

One can always argue that energy has always been abundant in nature. However, availability itself alone does not guarantee abundance. Rather, it is the ability to utilize this energy that characterizes abundance. Thus, we define abundance of energy as adequate production of useable energy, which is available, accessible, cheap, transportable, transferable, and scalable.

The transferability of energy would lead to a global scenario that ensures that energy can be evenly distributed. The scalability would lead to a scenario where energy can be utilized from small-scale application to large space exploration. These assumptions serve as the foundation for the further analysis.

1.2 Road to Abundance

How do we achieve this radical abundance of energy? We can view economic history as a series of technological revolutions that each enabled the subsequent revolution. Advances in agriculture allowed a small portion of a population to feed the entire population, thereby enabling urbanization and industrialization. Industrialization allowed the mass production of complex goods, thereby enabling the cheap manufacturing of powerful computers. Computation devices allowed efficient creation, storage, and distribution of information, thereby enabling dramatically more efficient learning, communication, and collaboration (Internet + globalization). Internet and globalization set the stage for energy abundance [3].

The present moment is a tipping point, in which decentralized transmission networks, cheap photovoltaics, sophisticated low-energy appliances, mobile phones, and "virtual" financial services are all merging to create a super-grid that will shift the energy paradigm [1]. These disruptive technologies increase access to basic electricity services. The smart grid will use the Internet as its control location. Like the cloud, it will store energy anywhere in the grid. Energy will become a social phenomenon, as Internet is today [4]. Everybody will be a both a consumer and a supplier of energy. Energy will be stored anywhere in the grid, and energy exchange will happen in a mesh.

The abundance of energy will be a result of the Internet of energy architecture, and a series of technological innovations in different solution areas. The energy efficiency of electrical utilities will increase. The efficiency of solar energy will increase, and cost will decrease. The amount of solar energy we can harvest on Earth is somewhat limited by varying cloud cover and the cycle of night and day. Space-based solar harvesters in orbit, on the Moon, or elsewhere in space will collect solar energy and transmit it back to Earth [5]. In 2065 we will be able to produce hydrogen through the electrolysis of water by overcoming today's problems—today, the process consumes more energy than it supplies.

Although nuclear fission produces a great deal of energy without relying on fossil fuels, it also produces nuclear waste. Nuclear fusion generates significantly less waste without all the radiation. In fusion process, fusing together light atoms into a heavier one at extremely high pressures and temperatures produces energy. Although fusion energy was already achieved even in the early 1970s, only recently did a fusion reaction produce more energy than was needed to start that reaction. A recent experiment at the Joint European Torus fusion reactor in the United Kingdom produced 20 million joules [6]. The ITER Tokamak fusion reactor is designed to produce 500 MW of output power with 50 MW to operate. Construction of the ITER Tokamak complex started in 2013 in Cadarache, southern France, and expected to start plasma experiments in 2020, with full deuterium-tritium fusion experiments starting in 2027 [7]. A Lockheed Martin research team has been working on a scalable compact fusion reactor, which will be small and practical enough for applications ranging from interplanetary spacecraft and commercial ships to city power stations [8].

The fusion reactor is considered very safe, as it requires extremely precise and controlled pressure, temperature, and magnetic field parameters to operate. Any deviation from the optimal condition will render it unable to react or to produce excess heat, consequently requiring no elaborate failsafe mechanism. There is no risk of a runaway reaction, and day-to-day-operation of a fusion power station does not involve the transport of radioactive materials and leave long-lasting radioactive waste to create a burden on future generations [9].

The basic fusion fuels from which deuterium and tritium are extracted and generated are water and lithium. Approximately 70% of the Earth's surface is covered by water. There is enough deuterium for millions of years, and enough easily mined lithium for several hundreds of years [9]. Also, fusion inflicts very low global impact on the environment, as it does not involve the emission of carbon dioxide (CO_2) greenhouse gas. A 1,000-MW electric fusion power plant would consume around 100 kg of deuterium and 3 tons of natural lithium in a year while generating 7 billion kilowatt-hours (kWh) of energy.

As R. P. Siegel puts it, "In many ways, fusion power seems like the perfect energy source. It's clean, it's inexpensive, and it uses seawater as its fuel source. It's the Holy Grail, it's the pot of gold at the end of the energy rainbow, and it has no appreciable side effects, except for one: modern civilization on steroids" [10].

1.3 Dynamics of the Energy Abundance

To examine the impact of the energy abundance on a global scale we look at two interesting restrictions: the nature of ownership and distribution of energy solutions, and the environmental impact such energy solutions create.

How does a future energy solution develop, and what will be the nature of the technology that determines technology ownership and distribution? If the technological breakthrough occurs as a simple and imitable technology, the ownership will be of more decentralized nature. However, if the scale of investment required in developing energy technology and producing energy is substantial, requires high-level operational expertise, and is difficult to imitate, the energy production might be more centralized. In such a case, the energy market might converge toward an oligopoly structure. Energy abundance, cheap unlimited energy, and oligopoly market structure might be against all economics odds.

One needs to add a few facts to reverse such odds. First, unlike in traditional economic theories, the energy producer will be capable of producing energy in unlimited quantities with very low marginal cost. Second, owners of fusion technology would have to dig deep in their pockets to develop it. However, at the beginning phase such technology will be facing stiff competition from alternative energy production from shale gas, other fossil fuels, existing nuclear technology, and improved renewable technologies. In such circumstances, to wipe out and win the competition, owners of fusion technology will have incentive to provide energy at cheaper price. Further, such endeavors will be favored by very low marginal costs of production. Third, owners of such technology will be able to create very strong barriers to market entry when they couple huge upfront investment with lower price. Thus, there will be enough incentives for the fusion technology owners to provide abundant energy.

On the other extreme, such energy technology might be developed as simple technology that does not require massive investment and is easy to imitate. Under such circumstances more entities would be able to develop and implement energy technology. This would also lead to a more decentralized and distributed market structure. We believe that development of this nature will provide an ideal platform for the favorable energy abundance scenario.

A decentralized market structure provides more safety from market collusion and other forms of market irregularities. In this study, we depict centralized energy technology distribution as unfavorable and decentralized technology distribution as favorable variables of the future scenario.

Energy has not only fueled the advancement and amenities of modern life but also brought some serious environmental consequences. Extensive use of fossil fuels as source for energy production has escalated greenhouse emission and also global warming. Since the Industrial Revolution in 1790, and accelerating since the mid-20th century, the burning of fossil fuels has caused Earth's surface temperature to rise. The combined effect has led to the climate change. What ever the energy production technology is, there is always a possibility of negative environmental impacts. Currently, the renewable energy source of hydropower is examined for its negative impact on water ecology, and nuclear energy sources are criticized for nuclear waste.

To achieve maximum benefits from the energy abundance, the future technology should have minimum environmental burden or the environmental impacts should be well negotiated. The environmental impacts from the use of resources place restriction on the abundance and its potential benefits [11].

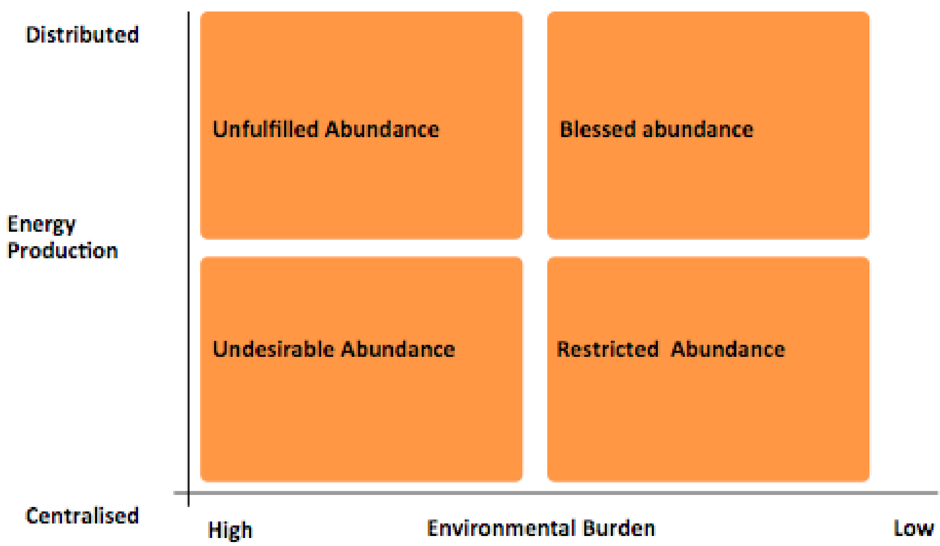

Figure 2. ***Future energy abundance scenarios.***

Considering these two dimensions of technological distribution and environmental burden from energy production and use, we visualize four alternative scenarios (Figure 2). In an ideal world, the energy production capabilities are not centralized and distributed. Further, the production and consumption of energy is not constrained by environmental consideration. We call this case *blessed abundance*. On the other extreme, the least desirable scenario, the energy production technology is centralized such that it poses looming political and economical threat to sustainable and full-fledged abundance. Further, use of energy abundance also has negative impact. This is called *undesirable abundance*. In other alternative scenarios, either the technological distribution is restricted (*restricted abundance*) or the use of energy is cursed by environmental implications (*cursed abundance*).

In this article we have a closer look at the scenario of blessed abundance. We picture the world 50 years from now, in 2065. The world will be blessed with the abundance of energy supplies and advanced technological development. We call this state, according to Bob Metcalfe, "squanderable abundance," because we will have more energy than we need. What happens to humanity when we have hundreds of thousands of terawatts of energy available? In the words of Sterling D. Allan, "Free energy will promulgate a forward leap in human progress akin to the discovery of fire. It will bring the dawn of an entirely new civilization—one based on freedom and abundance" (Feb. 2003).

2 *Squanderable Abundance*

With squanderable abundance, energy becomes the fuel that allows us to fulfill almost all of our dreams [12]. We start looking at those dreams by analyzing the direct implications of the energy abundance.

2.1 Water

The water crisis is the number one global risk based on impact to society (as a measure of devastation), and the number eight global risk based on likelihood (likelihood of occurring within 10 years) as announced by the World Economic Forum in January 2015 [13]. Although water is abundant almost everywhere, clean, drinkable water from natural sources is shrinking drastically. However, if cheap technology is available in order to purify water from available sources, the water problem will be resolved. Due to cheap transportation cost, water plants can be established near or at the sea and clean water can be transported in any part of the world. Abundance of energy can easily mitigate shortage of clean water, as simple solutions can be devised to desalinate seawater with abundant energy [14].

Groundwater is another vast source of clean water. In the post–energy scarce world, this huge source of water will be in use with ease. Availability of abundant clear water will bring great positive change to the ways life is lived, especially in the developing countries [15,16].

2.2 Food

Accordng to Food and Agriculture Organization (FAO) of the United Nations, energy is closely related to food security, poverty eradication, and better nutrition. Food systems consume 30% of the world's total consumed energy; hence, energy is a very important factor in determining food price [17]. Cheap and abundant energy directly affects the food price. Until now food production was heavily dependent on the weather, for example, the position of the sun and amount of rainfall. As a result, throughout the year a big part of the world was unavailable to be used for food production. For example, the Nordic land was arable only during a very short summer. And the agricultural systems in the developing countries near the equator also depended greatly on the amount of natural rain.

Abundance of energy nullifies these dependencies and makes it possible to produce food anywhere throughout the year, disregarding the weather. As a result, food can be produced not only in the traditional arable land throughout the year, disregarding the harsh weather, but also in the harsh environments, such as a plateau or desert, or even in riverbeds, seafloors, and underneath the Earth's surface. It requires initial investment to build the infrastructure. However, low production cost, cheap transportation, and robotic labor reduce the cost significantly.

Abundance of energy also brings down the cost of harvesting and post-harvest technology, for example, solar crop driers and refrigerators. Availability of such machineries reduces huge food waste by enabling efficient crop collection, safe storage, and affordable transportation. This not only increases food volume but also improves food quality.

2.3 Transportation

Commercial transportation takes 27% of total energy consumption of the world [18]. Energy abundance will reduce the transportation cost significantly. This significant reduction in transportation cost will bring successive reductions in all walks of life. For example, the reduction in transportation cost will reduce production cost of transportation vehicles by reducing the transportation cost of raw materials that will in turn reduce transportation cost further. With great reduction in transportation cost, the transportation system of tomorrow will be redefined. It is more probable that personal aerial vehicle (PAVs) will be used to travel short to medium distances, such as from home to office, and high-speed ground transportation will be used for long-distance travel.

Some revolutionary systems and solutions have already been proposed for high-speed ground transportation. Maglev (derived from magnetic levitation) is a transport method that uses magnetic levitation to move vehicles without them touching the ground. With maglev, a vehicle travels along a guideway using magnets to create both lift and propulsion, thereby reducing friction and allowing higher speeds. A current version of maglev in Japan has already attained a speed of over 600 km/h. ET3, an organization connected to the Venus Project, has been promoting a tube-based maglev that can travel up to 4,000 miles per hour, in a motionless, frictionless tube, which can go over land or underwater. This technology will make it possible to go from Los Angeles to New York for an extended lunch break, or from Washington, D.C., to Beijing, China, in 2 hours. This is the future of continental and intercontinental travel. Elon Musk has come up with a concept of high-speed transportation system called Hyperloop, whereby pressurized capsules ride on a cushion of air that is driven by a combination of linear induction motors and air compressors [19].

With energy abundance, the major constraint of the cost of energy will be out of the play, and availability of cheap vehicles thanks to low production cost will accelerate the advent of a new era for personal transport systems. Already, research on the means to “lift personal transportation into the third dimension” has garnered huge amounts of attention [20,21,22]. MyCopter, a project funded by the European Union (EU), is working on a personal air transport system (PATS) based on low-altitude PAVs envisioned for traveling between homes and working places in urban environments. The Advanced Air Vehicle Program (AAVP) of the National Aeronautics and Space Administration (NASA) is looking into fixed-wing and vertical-lift aircraft as well as exploring far-future concepts that hold promise for revolutionary improvements to air travel [23]. In addition, research on advancing wireless energy transfer technology [24] and low-latency ultra-reliable networks [25] has also garnered much attention, both in academia and industries. The PAVs will be provided with energy from ground wirelessly, and the driving and navigation system will be totally shifted to the next-generation wireless network. Note that the driverless car is already a reality today.

It may not be very far in the future when flying cars/PAVs will be parked in the lower space. Wireless lift will be used to board the vehicles. Once boarded, the passenger(s) will require only giving the location of destination and pay some amount for the trip, without thinking about navigation and refueling. The PAVs will use their own power source to reach highways and then get wireless power from the 3D highway system.

2.4 Labor

Given the pace of current technological advancement, we believe that robotics technologies will accompany the abundant energy scenario. This leads to an optimal production scenario in which availability of unlimited low-cost energy and superior operational efficiency will boost production, transportation, and agricultural efficiency in an unprecedented way. As a result, job markets will see important restructuring. The routine jobs that do not require human judgments and interventions but mostly entail activity to be executed repeatedly will be the first candidate to go to the robots. Again cheap energy will ensure that programmed machines as a workforce come at better price. Thus, for labor-intensive jobs, humans will be set to take a back seat and look for alternative careers.

Jobs that require technical expertise, creativity, and non-routine judgments will be the ones that people might aspire to hold. Further, service-oriented professionals, such as doctors, teachers, and lawyers, would be of increasing importance. Machines doing basic jobs will also mean that many jobs that exist today will be extinct. In such circumstances, a big challenge for economies will be keeping the unemployment rate down. Economies will be required to invest substantially to train and educate people. The countries that train and develop the workforce for skilled jobs, such as designing and maintaining sophisticated machines or writing the code that helps them run, will have substantial competitive advantages over others [26].

3 Impact to Our Society

3.1 Post-Scarcity Economics

There are four kind of costs associated with production: energy, labor, time, and resource costs. Everything that we use consumes energy to be produced and transported. For example, energy represents roughly 50% of ocean shipping costs and 40% of aluminum production costs [27]. As a result, reduction in energy cost will cause cycles of successive cost reduction. *The Economist* predicts that within the next 20 years, half of all jobs will be taken over by machines. In some highly automated industries, like the automobile industry, it might be even up to 90% [28]. The ability of machines to work even in unfavorable environments for long hours will bring labor and time costs down. A non-human workforce, abundance of energy and raw materials, and the advent of efficient production technology will enable conditions of material abundance, which in turn will enable free distribution and complete a fully developed post-scarcity economics.

When energy is readily and cheaply available, with robots providing a cheap and reliable labor force, one might argue that the natural resources will be depleted at an exponential rate. The future market will be redefined by relentless production and consumption. At the same time, mining and resource exploration will also become more expansive. By the virtue of cheap and abundant energy, governments will be able to deploy more resources to explore new sources of material that otherwise would have been inextricable. Thus, increased consumption will be accompanied by added sources of natural resources from more exploration and new methods of growing foods, as discussed earlier. Reduced transportation cost and reduced lead time will further drive up the urge for sourcing. Increased food and material sourcing will lead to future globe where countries can focus on specializing in certain areas of production or as a source of raw materials.

Overcoming the hurdle of energy limitation would also mean possibility of developing material recycling technologies that otherwise would be far fetched. Material recycling technology could act as a closing loop in production system that injects used material back as raw material. The recycling industry coupled with reverse logistics, enabled by the grace of cheap energy, would be acting as a new source of raw material supplies in the production loop. These recycling businesses will also be a standout for the investors. The resulting consequences will be reduction in waste and also severe penalties on the wasting of resources.

In an alternative scenario, a shift in business model from product ownership to product leasing might emerge in the production system. Currently, consumers own the product. However, pressure to be material-efficient might cause business to shift the business model so that the producing companies own the product and customers use it by making leasing contracts. The company is responsible for maintaining the product and the customer pays leasing fees for the use of the product, thus creating a circular economy. However, the circular economy will still need to integrate recycling in its structure. Further, the resource pressure in the future might lead humans to space exploration in search of resources.

In post-scarcity economies—with diminished energy, labor, and transportation costs; reduced lead time; and better sourcing—the resultant effect would yield very cheap foods and products. Thus, we can visualize a future globe where energy-driven economic sectors such as production and transportation gain enormous production and operational efficiencies. The global food and product markets will be more affordable and accessible than ever. With the falling prices of foods and products, courtesy of the peaking efficiencies, one could rush to the conclusion that future economies will contract due to decreasing prices. Despite the falling prices in food and products, the towering shares of the service and entertainment sectors of the economy will, mostly, compensate the economic growth. Undoubtedly, the economies will be flooded by commoditized products, thanks to the unprecedented efficiency that we will achieve. At the same time, cheaper products will also mean that consumers will have higher discretionary income left to spend. The products that are considered luxurious now will be commoditized. As a result, increased commoditization of product will result in lucrative growth of luxury products, services, and entertainment. Products that are endowed with art, design, and creativity will continue to command luxury position and premium revenue. Entertainment, tourism, and sport industries will flourish to a new height. Thus, as consequences of falling prices of food and products, service sectors will experience explosive growth.

3.2 Liberalization

The energy abundance will lead more countries down the path of economic openness and liberalization. The developing nations that are in dire need of external financial injection in the economy will have to open up and liberalize themselves to benefit from the vast potential of the energy abundance. As present, there lies a wide disparity between countries in terms of economic and financial capacities. The developing countries are still far from achieving the growth and development levels of their Western counterparts. The sluggish economic growth can be partly explained by the fact that these developing countries have failed to meet the energy needs required to the drive up the economy. Maximizing the utilization of energy, to propel the economy, requires substantial investments in building infrastructures and establishing the industries. However, government can break the investment hurdles by opening the market to the private and foreign investors. Further, developing countries are also lagging behind in terms of access to the modern technologies. In such circumstances, foreign direct investment, as always, will act as an important tool to gain access to the technology. Given the robotic revolution and automatization in economics sectors, the stakes for liberalizing economies are set to be even higher. One can only imagine that more economies will be lured into economic openness and liberalization once the abundance of energy rises to the horizon. The outlook of the global economy in the future will be more open and liberal than ever.

3.3 Technological Singularity

"If very complicated chemical molecules can operate in humans to make them intelligent, then equally complicated electronic circuits can also make computers act in an intelligent way" —Stephen W. Hawking, physicist (1998).

Technological singularity has been predicted as early as 2030, when the intelligence of computers, computer networks, or robots would enable them to redesign themselves for self-improvement. Robots operating with such strong artificial intelligence (AI) will not only rival human beings in terms of intelligence and creativity, but the repetition of such cycle—that is, the machine or machine-assisted human being designing further intelligent machines—may result in an intelligence explosion [29]. It is predicted that the end product of such a chain will be something that is unfathomable with current knowledge. Currently, opinions are divided more on the ramifications of the emergence of such super intelligence than on the inevitability of its emergence. If the avoidance of potential hazards and pitfalls can be ensured, this will surely expedite the ongoing journey of technological civilization at an unprecedented pace when coupled with energy abundance.

3.4 Exploring Space

As most of the problems of the current world will be resolved by both the direct and indirect influence of energy abundance except the available space on this planet, it is safe to assume that energy abundance will rejuvenate the race to conquer space. Unfortunately, with the closest star, Proxima Centurai, being 4.24 light years away, the travel time will be enormous unless spaceships attain a travel speed that is at least a significant percentage of that of light. Along with other issues, the requirement of the sheer amount of energy needed for such a voyage and a feasible propulsion system are two major hindrances for interstellar travel. It has been theorized that fusion rocket starships with a large number of stages of nuclear fusion reactions can achieve speed arbitrarily close to that of light [30]. Even if technologies like EmDrive (i.e., radiofrequency resonant cavity thruster) ultimately fail, energy abundance is expected to open the door to a new era of technological excellence. It won't be long after energy abundance when a generation ship with a modern Columbus or an egg ship with frozen early-stage human embryos along with highly intelligent and trained robot parents will leave this planet to find a new home in the heavens. With energy abundance, colonizing the Moon or Mars will be achieved within a reasonable timeframe. In that case, this new land can be used to test the extraterrestrial human civilization and as the center for space exploration.

3.5 Societal and Cultural Implications

According to Pritzker [31], energy enables us to live healthful, fulfilling lives. Energy is used to power our homes, grow our food, and manufacture our clothes and other basic necessities. Energy let us communicate with friends and family, travel abroad, and commute. Energy liberates especially women and children from the drudgery of manual labor. In both the developed and developing worlds, energy is critical for clean water, healthcare, reliable lighting, and transport and telecommunication services. Countries that can meet their energy needs become wealthier, more resilient, and better able to navigate social environmental hazards.

Megatrends affecting future development include the dynamic of technology, the transition of service society, environmental awareness, and the aging population. In addition to this bottom-up approach, peer-to-peer models of organization where individuals organize their joint efforts in open cooperation and *prosumerism* will increase [33,34]. Prosumerism (producer + consumer) refers to consumers and citizens turned to active producers. In practice, peer-to-peer models can mean, for instance, social media networks, open source programming communities, grassroots political movements, consumer movements, and co-working spaces [32,33].

The population is aging rapidly, which increases the need for assistance and care services to support the daily living of the aging population. Not just the elderly but also the younger generations increasingly demand new services to support and ease their everyday living as household demographics change, as urban lifestyles develop, and as the values of service consumption evolve.

We will live longer and stay healthy. The aging of the world's population in developing and developed countries is an indicator of improving global health [34]. However, the main health burdens for older people are from chronic diseases. The need for long-term care increases. Many of the very old lose their ability to live independently because of limited mobility, frailty, or other physical or mental health problems.

In 50 years, family structure may be very different in form than that of the family of 2015. Two adults and children principally form the family structure in 2015. The traditional family of mother, father, and children may vary to include numerous varieties of diverse familial arrangements. Gay-parent, single-parent, and grandparent families will prosper in 2065. Although the members of the 2065 family may differ, the love between the family members will not. Families will adapt and shape society around the needs of the family. Families will make sure the needs of their children are met through community action.

The global learning environment will enhance a student's understanding about the world in 2065. The need for self-education will not diminish even when there is energy abundance. The population will be highly educated, and perhaps the working mode will be different from how it is now. For example, especially for creative workers, where the shift occurs from working mode to leisure time, it will be difficult to determine such mode. As there is no need for mundane work in 2065, because robots are doing the routine jobs, there will be more time for entertainment and intellectual debate.

4 Environmental Implications

Scientists at the Stockholm Resilience Centre have identified nine planetary boundaries (see Figure 3) that define the envelope within which we must conduct our affairs if we are to avoid destroying our very source of sustenance. In addition to climate change, there is also biological diversity, nitrogen and phosphorus consumption and release, ocean acidification, stratospheric ozone, land-use change, freshwater availability, aerosol loading, and chemical pollution [35]. We need to respect all of these boundaries in order to maintain the comfortable living conditions we enjoy now. With fusion energy and provided that we will be able to manage heat economically, the future looks bright. Also, in terms of respecting these environmental boundaries, we will better off than is currently the case.

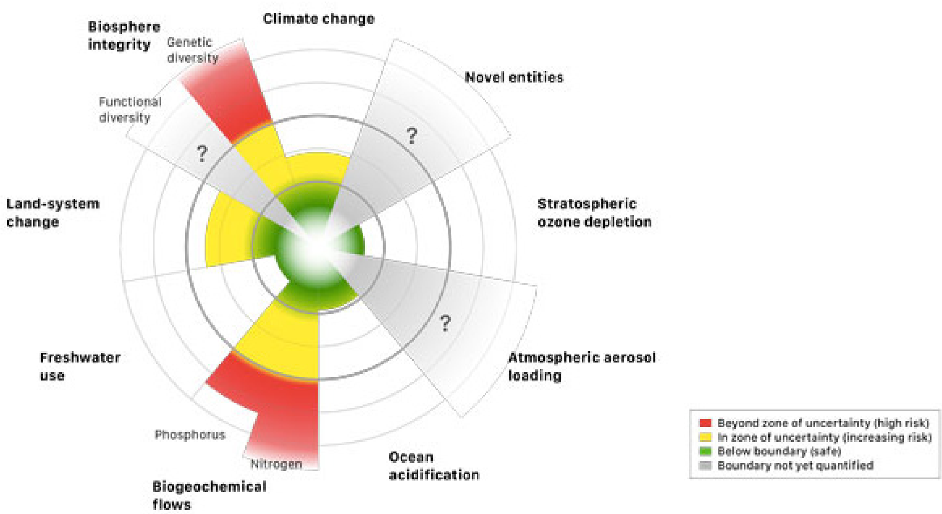

Figure 3. ***Estimates of how the different control variables for seven of the nine planetary boundaries have changed from 1950 to present. The green shaded polygon represents the safe operating space [35].***

Energy consumption has always gone hand in hand with material consumption, resource depletion, and environmental pollution. However, energy abundance occurring via fusion combined with technological advancement will ensure that future will have a different outlook. The fact that use of fusion to produce energy will not emit harmful gases like carbon dioxide and carbon monoxide will be instrumental to controlling air pollution. Transportation and industrial sectors, which have been dependent on fossil fuels, can be greener and cleaner with the use of fusion energy. Further, it would put a brake in further depletion of ozone layer. In fact, fusion energy might be the world's only chance of avoiding catastrophic climate change caused by global warming [36].

The massive jump in consumption patterns in a post-scarcity scenario means materials will be among the valuable resources. Thus, the penalty for wasting materials and resources would be pivotal for controlling material waste at the source. The emergence of a circular economy and pervasive material recycling technology will also equip us with the capability for better material waste management. Better waste management will automatically lead to reduced land and water pollution. Abundance of energy can further lead to development of air and water purification technology.

Along with all the positive environmental implications, energy abundance can still have some serious challenges to overcome. Even with clean technology like fusion, heat emission is likely to be major issue. Given the fact that global warming is already a big challenge, this makes it look like a condemnable threat. The enormous consumption of energy will surely produce a huge amount of heat that needs to be managed. The heat management can have both environmental and economic implication. On one hand, unmanaged heat can lead to severe environmental consequences in terms of global warming and ecological damages; on the other hand, it will require substantial resources. The additional resource requirements will add to the cost of energy production and, ultimately, limit the full-fledged benefits of energy abundance. Thus, the nature of heat management is a critical consideration.

5 Summary

The dawn of human civilization was proclaimed when humans learned how to control fire—that is, use energy. The adoption of better means regarding how to produce and utilize energy have ushered in a human life of comfort, ease, and luxury, and enabled the transformation from a "cave inhabitant" to the one heading for other galaxies. With energy abundance, there will be a tremendous change in the way an individual lives his or her life from the way the world runs today. We will not have scarcity of food, water, shelter, raw materials, manual labor (i.e., robots), or even processing power (i.e., strong, AI-driven supercomputers). The wars over energy sources or trans-river boundaries, that is, water sources, will be no more. As a result, the energy abundance will have an enormous potential to change the world.

However, deliverance of that potential primarily depends on the emergence of humankind as a global community with a global political will. Note that richest 1% now owns more wealth than the bottom 90% in the United States. Even in last 4 years, 80 of the world's top billionaires have doubled their wealth, and currently their wealth equals that of the bottom 50% of the rest of the world [37]. If such a trend continues, or if few countries and corporations manage to control the whole energy system and consequently other production systems, energy abundance itself may not bring any positive change to the world. Rise of machines as workforce may render most people jobless, and the resulting extremely low purchase power may make energy and material abundance irrelevant to a large percentage of people. In short, it depends on the political will of the global body whether the machine will work for humankind, giving them freedom from manual labor, or whether the machine will be used to rule them in the energy-abundance-enabled, post-scarcity world. However, we believe the explosion of social media through the Internet and future versions of such communication systems will not only bring people from different corners of the world closer and make them citizens of a global village, but also empower the masses of people and give them substantial and direct access to policymaking.

Additionally, abundance of energy along with a non-human workforce may spur the indiscriminate and unscrupulous utilization of available resources. If the production of this enormous energy does not come from clean sources or if the use of this energy causes environmental pollution, it may take the planet to the brink of instability and natural calamity. The climate may undergo drastic and irrevocable change; ecosystems of diversified flora and fauna of the planet will be threatened.

In the age of such abundance and prosperity, humankind may not converge on political or economic ideologies, and diversity of thoughts on these aspects may still be considered as beauty. However, consensus on how and at what pace the natural resources will be utilized, how fast the civilization will be allowed to flourish, and what costs will be conceded for such advancements will be mandatory in order to preserve the world as a livable habitat for next generations.

Acknowledgments.

We thank warmly Ms. Sirkka Heinonen, Professor and Director at the Finland Futures Research Centre (FFRC), for her valuable help in the scenario building.

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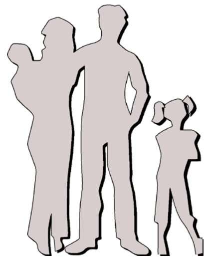
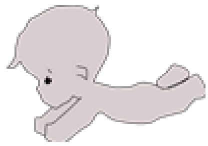
Appendix: Scenario in 2065

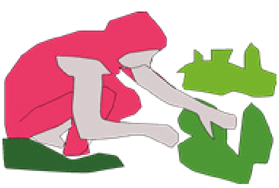


In 2015, Maija, 35, lives with her husband Esko, 34, and their newborn child Samuel, 6 months, in Töölö. Apart from his new family, Esko has a daughter Milla, 8, from a former relationship. Milla stays every other week at her father's in Töölö and every other week at her mother's in Sipoo, where she goes to school. Thus, during every other week, Maija and Esko have to transport her to school in Sipoo, taking much time. The family keeps contact with Milla through Skype, and from time to time they play hide and seek through Skype connection. Maija and Esko and their children spend time in their summer cottage in Kemiö; this summer cottage has belonged to Maija's family since 1900 and they have had solar panels for some years now.

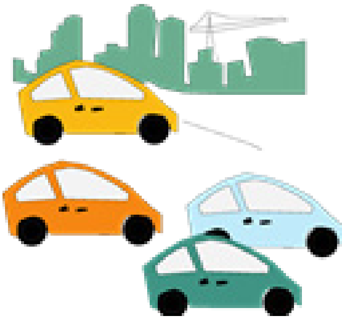


Communication today is mostly through social media with digital and electrical devices. It depends your age whether you use WhatsApp or Facebook or SMS for sending updates of your life and for capturing the moment and sharing—you might use Instagram for ad hoc picture delivery and/or get inspired by Pinterest. Maija is on motherly leave and spends most of her time at home with baby Samuel. At the moment, Samuel is spending most of his time sleeping and eating. His mother has time to update the blog she started to keep since she found out that she was having a baby. This is something she wants to share later with her son. She has learned from Milla how to use WhatsApp and Instagram, which are free to use. Besides that, Maija is keen on tracking energy consumption at home and at the summer cottage, and from time to time she changes the consumption pattern accordingly as needed.

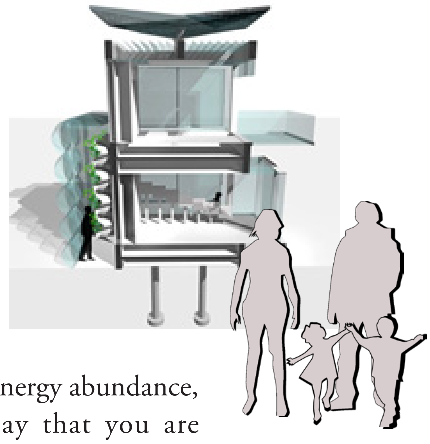
When the family spends time at the summer cottage, they treasure family traditions such as growing their own food, picking berries, fishing, and sometimes hunting. Maija has increased her interest in where the family's food comes from, and today she prefers to eat local food that is most often produced, processed, distributed, and consumed within a smaller, defined area. She even has her own vegetable patches. She is considered self-sufficient for necessity items, as it was a hundred years ago.



In comparison to life more than a hundred years ago, our lives now are delightfully luxurious. Those born during the last century were more concerned with survival than living standards. There was constant lack of necessities and hardly any leisure time, except Sundays. Individuals worked to meet basic needs like those for food and shelter, and families and neighbors provided tight-knit communities filled with work and belongingness. Education was entirely dictated by the social class you had been born into.



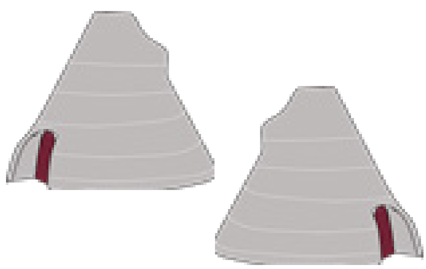
Today, Esko is working for the advanced Company Z. The company offers good benefits, and a company car is included. This car uses electricity. Shared transportation gives a good option for Maija to travel short distances, as they have only one car, and it provides a good opportunity to reduce the reasonable expenses of traveling. Shared transportation is a demand-driven vehicle-sharing arrangement, in which travelers share a vehicle either simultaneously (e.g., ride sharing) or over time (e.g., car sharing or bike sharing), and in the process share the cost of the journey, thereby creating a hybrid between private vehicle use and mass or public transport.



Meanwhile, when the family is not at home the Hoover robot is chasing after the dust on the floor.

In 2065 Samuel is now 50 years old and he has his own family—his wife Sofia and their twins Ariel and Amos. The twins have moved from home to live abroad in order to have new kind of perspective on life, where they will nourish their intellectual curiosity. Actually, after the energy abundance, you can't really say that you are traveling because everything seems to be so near.

Samuel travels short to medium distances with a personal aerial vehicle (PAV) similar to MyCopter, and if he has to travel long distances he uses the high-speed ground transportation system, which is similar to Hyperloop. The roads and streets expanded vertically and the low-altitude space has routes to follow.



The family lives at the same place where they used to have the summer cottage when Samuel was still a child. People have started to escape back to the countryside, where they have fresh air and enough space to express themselves. There each family member has his or her own cabin, and the cabins are linked together. They have very lively social circles, a kind of "MyTribe."

Samuels's family eats fewer processed foods and eats food grown closer to where they live. Abundance of energy ensures the availability of required water throughout the year. As a result, food can be produced not only in the traditional arable land throughout year, disregarding the harsh weather, but also opens up the door to new and exciting ways of doing this.

In the society's circular economy, nearly everything can be recycled and reproduced again. Samuel is able to wear clothes chosen by his MyRobot maid, or he prints them with the techniques of additive manufacturing, which starts with loose material, either liquid or powder, and then builds it into a three-dimensional shape using a digital template.

Meanwhile, when Samuel is at MyHome he prefers to do the simple stuff, like fishing or hunting, or just enjoy the possibilities life has to offer.

Scenario pictures from http://www.ikeadecoration.com/wp-content/uploads/2014/12/33f77__Top-28-Future-Gadgets-And-Appliances-Concepts-For-The-Home-Of-2050-homesthetics-25.jpg, and http://montaukvacations.com/scienceifl/images/myCopter.png. Illustrations by Renita Niemi©.

Fossil Fuel Divestment: Money and Morality

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Abstract: This article explores the reasoning and feasibility of fossil fuel divestment, an issue that has recently attracted attention from both financial and civil society actors. We first explain the background of the increasing awareness by investigating the international climate change negotiations, the aim to halt global warming to 2°C, and the consequences of this target for fossil fuel assets. Analogies are drawn from previous divestment campaigns on tobacco and apartheid. Financial and moral perspectives of fossil fuel divestment are explored, and the action of financial actor Nordea Bank and the civil society's role throughout the divestment campaign identified. From these premises a conceptual framework for fossil fuel divestment is drawn and future scenarios presented. The study concludes that in the case of fossil fuel divestment, money and morality are not mutually exclusive.

Keywords: fossil fuels, divestment, financial institutions, NGOs, climate change, energy

1 Introduction: Divestment—What Is It All About?

Divestment from fossil-fuel-based companies has gained attention in recent years, alongside the global awareness of dangers of carbon emissions and climate change. In sight of global government agreements to combat climate change, the resulting mandates and macro political interventions have imposed great pressures on the worth of fossil fuel assets. Thus, the divestment from fossil fuels may be financially feasible. However, discussions in this subject are rife with ambiguity and misconceptions, and made even more complicated by the fervent emotions often involved in climate change issues. In this study we aim to demystify the divestment of fossil fuels through a thorough investigation of different perspectives. Our approach is broadly a two-pronged investigation, one of ethical humanitarianism (morality) and one of economic sustainability (money), both aspects being significant in the discussions surrounding divestment. In understanding concerns from these two main perspectives, we seek to formulate a more accurate and well-adjusted opinion regarding divestment from fossil fuels and campaigns surrounding it.

Divestment is defined as the intentional withdrawal of investment capital to discourage the associated cause of the benefactor. It needs to be clarified that divestment does not concern the reinvestment of the divested funds; thus divestment from fossil fuels does not directly imply the active reinvestment into benefactors affiliated with renewables, however likely this consequence may seem. Nonetheless, it is well acknowledged that divestment from fossil fuels releases additional funds, which creates the opportunity for investment in sustainability-related stocks, thus promoting the growth of that particular market. Currently, the investments in renewable energy are still less than that of fossil fuels. The "450 Scenario" is a reference scenario studied in the annual publication *World Energy Outlook* by the International Energy Agency (IEA). The report suggested an energy pathway consistent with the goal of limiting the global temperature rise to 2°C by reducing the concentration of greenhouse gases in the atmosphere to around 450 parts per million of carbon dioxide (CO_2). To meet the 450 Scenario, it is estimated that investment in energy efficiency has to be eight times larger than it is today, and investment in low-carbon power generation has to be increased by a factor of three. [1] Thus, there must be an increase of USD 0.41 trillion in 2013 to USD 2.3 trillion in 2035 to achieve the 2°C target. Therefore one can observe a clear investment gap with respect to non- and low-carbon industries. It is unclear whether the estimation of the investment gap requires first divesting funds from fossil fuels and diverting these funds to sustainable energy markets, or whether the estimation is more conservative and accepts the current investments in fossil fuels, so that it would already be enough to have the additional investments in sustainable markets. Either way, divestment from fossil fuels will benefit the cause, at the very least, as alluded to earlier, by making additional funds available and creating the opportunity for these funds to be reinvested into sustainable energy markets.

We start our discussion by introducing the history and current state of global climate negotiations, which are causing the pressures to reduce the use of fossil fuels. In this process, we discuss concepts such as the carbon bubble, stranded assets, and sin stocks, with reference to divestment of fossil fuels. We introduce a multi-level perspective (MLP) model, which has been used to describe socio-technical changes in sustainable innovations and transitions within society. We will later use this model to assist the understanding of fossil fuel divestment, and discuss the possibilities of societal change regarding such sentiments. Before the investigations into the current affairs of fossil fuel divestment, we first take a look into the past. We present two well-known past divestment campaigns (tobacco industry and apartheid in South Africa), which have inspired the current fossil fuel divestment campaign and provide analogies on how the movement might progress. The development trends of these cases, as well as the social, economic, and political factors, can be then compared to the current fossil fuel divestment. As mentioned to earlier, we isolate our investigations into two parts, the financial and the moral perspectives, each championed by different actors. The financial investigation covers a numerical analysis of the financial feasibility of fossil fuel divestment, coupled with an in-depth current case example of Nordea Bank, whose decisions and reasoning behind divestment are explicated and discussed. The Nordea case is based on an interview held with Antti Savilaakso (director of responsible investment in Nordea) [2], a lecture held by Antti Savilaakso at Aalto University, as well as published news material. Thereafter, we progress to the moral perspectives and scrutinize the civil society and campaigns of nongovernmental organizations (NGOs) with respect to their ethical reasoning behind divestment. The campaign section is based on available campaign materials and campaign web pages, as well as field observations and discussion with activists on the Global Divestment action day in Helsinki, Finland. Finally, the findings from these investigations are discussed in the context of theory underpinned by the MLP model, with some other further deductions based on our analyses.

2 The International Climate Change Negotiations

The targets of international action have evolved a long way since the first climate conference organized by United Nations Environmental Programme (UNEP) and World Meteorological Organization (WMO) in 1979 in Geneva. The first international agreement on climate change was made in Rio de Janeiro in 1992, in the United Nations Conference on Environment and Development (UNCED). The purpose of the United Nations Framework Convention on Climate Change (UNFCCC) was to keep greenhouse gas emissions at a level that would not cause dangerous global warming. The aim was to ensure adaptation time for ecosystems, prevent dangers caused to agriculture, and ensure sustainable development of the economy. All countries were required to start monitoring, measuring, and reporting on their emissions to the secretary of the convention. The convention also introduced the concept of "mutual but shared responsibility." This meant that all parties had the same responsibility to protect the climate, but the needs of developing countries should be taken into account. It was agreed that industrialized countries will have the responsibility to lead the fight against climate change given their better capability to do so (in the original agreement proposal this leading position was justified by their historical responsibility, but this was changed because of U.S. demands). As a mid-term goal, it was also agreed in Rio that industrialized countries would freeze their emissions to the level of 1990 by 2000. However, this goal was not legally binding [3]. The convention came into force in 1994 and currently has 196 parties [4].

In 1997 the first legally binding quantitative targets were agreed upon. This so-called Kyoto agreement states that the industrialized countries should decrease their total emissions by 5.2% by 2008–2012. Separate country-specific percentages were listed (such as an 8% decrease for the European Union [EU]). There were no binding targets set for the developing countries. To come into force the agreement needed to be ratified by 55 parties emitting 55% of the emissions. This was accomplished in 2005 with Russia's ratification despite the fact that the United States had opted out [5].

The road to the second round of the Kyoto Protocol was not easy. The Copenhagen meeting in 2009 failed famously, producing only a loose climate accord. A bit more progress was made in the 2010 meeting in Cancun, Mexico, where the world leaders agreed to limit global warming to 2°C or less. The debate on whether the Kyoto Protocol has a future continued to heat the discussions. In 2011 in Durban, South Africa, the parties decided on a roadmap that would guide the decision making for a new global climate agreement that should be finalized in 2015 and would come into effect in 2020. This roadmap started to gain more interest than the Kyoto Protocol. The second round of the protocol was agreed on in Doha in 2012, but Canada, Japan, and Russia did not agree to join. This made it clear that the Kyoto Protocol would not deliver the 2°C target [6].

The new agreement was on the table in the following yearly summits in Warsaw (2013) and Lima (2014). Civil society actors have not been pleased with the negotiations. In Warsaw, 800 representatives of NGOs marched out of the meeting to protest the slow and quarrelsome process [7]. The civil society actors blame the world governments for not acting to fulfil their commitments to limit global warming under the agreed 2°C target. Their accusations were supported by the UNEP's Emissions Gap Report, which estimates that "emissions will rise to 55 Gt CO_2 in 2020 if countries do not go beyond their current climate policies." The same report states that to have a likely chance of meeting the 2°C target, global emissions should not exceed 44 Gt CO_2 in 2020 [8].

Although climate change negotiations have been proceeding slowly and at times there are more disagreements than solutions, there is a growing hope that a global climate agreement will be reached in the Paris Summit in 2015. The biggest conflicts are between industrialized and developing countries, especially on how the load of the mitigation efforts should be divided between them. This is illustrated clearly in the argument between China and the United States. The United States has not been eager to commit to binding emission cuts without China joining the efforts. Their agreement made in the end of 2014—in which China promised that its emissions would stop growing from 2030 and the United States responded by promising to cut its emissions by a quarter [9]—can be seen as a positive sign for the Paris meeting. The pressures are also rising from the business world, which is calling for better climate policies. The World Bank made an initiative in 2014 for global carbon pricing. The initiative is supported by 73 countries and over a thousand companies and investors representing 52% of the world's gross domestic product (GDP) [10].

3 *Carbon Bubble and Other Divestment-Related Concepts*

From the climate change negotiations, there is an ever-increasing urge for the reduction of carbon emissions. As mentioned, the 2010 climate meeting in Cancun, Mexico, resulted in the agreement that greenhouse gas emission should be reduced to avoid a temperature rise of more than 2°C above the pre-industrial levels [11]. However, in order to reach this target, it has been estimated that a third of oil reserves, half of gas reserves, and over 80% of current coal reserves should be left unused from 2010 to 2050 [12]. This naturally implies the possibility that the extraction and usage of 60% to 80% of oil, gas, and coal reserves may become forbidden [13], or at least greatly discouraged, from global policy perspectives. For investors in fossil fuels, this means that much of the fossil fuel assets of listed firms may become restricted, leading to either very expensive or risky stocks. Furthermore, the development of unconventional oil production techniques, as well as Arctic resources, is not in line with the 2°C target [12]. The decrease in demand for fossil fuels would most probably also result in decrease in prices, as well as a reduction in equity valuations by 40% to 60% [14]. Therewith arises the problem of the so-called "carbon bubble."

In financial contexts, the term "bubble" has been used to refer to a situation where an asset is regarded as being more valuable than it eventually turns out to be. The breaking of the bubble causes the stocks that are related to those assets to decrease in value significantly. Sometimes this can even cause a financial crisis affecting the whole society. The significance of asset bubbles comes from their disruptive potential and defiance of rationality [15]. With regard to fossil fuels, the term "carbon bubble" has been coined to describe the notion that carbon- or fossil-fuel-based assets are being valued more than their actual worth. This eventually results (however slowly or quickly this may occur) in the "popping" of the carbon bubble, causing the value previously bestowed upon those assets to nullify. Many arguments for fossil fuel divestment rest upon the ongoing realization that values of carbon assets are decreasing in reality. This goes hand in hand with "stranded assets," referring to the situation where fossil fuel assets become "stranded" in the ground due to a variety of reasons (including environmental risks such as climate change and water constraints) leading ultimately to unfavourable financial costs for these assets. Naturally, social norms or consumer behaviour might also lead to changes in asset values [16]. Stranded assets imply that they would suffer from unanticipated or premature write-offs, downward revaluations, or conversion to liabilities. As can be seen, then, fossil fuel divestment is ultimately driven by the perception of the value of fossil fuels and the costs of using them, both in terms of money and in terms of human moral responsibility.

Divestment from the perspective of moral responsibility relies mostly on what is considered wrong by society. In this context, the term "sin stock" is used [17]. Traditionally the term refers to stocks of companies that produce alcohol, tobacco, and gaming. These are companies making products that can be considered to have negative impacts on society. Research by Hong and Kacperczyk [17] concludes that institutional investors are less likely to invest in these alcohol, tobacco, and gaming companies. There is evidence that firms that score well in corporate social responsibility (CSR) get cheaper equity financing, whereas participating in two "sin" industries—such as tobacco and nuclear power—increases a firm's cost of equity [18]. Thus, financing institutions do seem to rate at least some sin stocks as having higher risks. Even though this may pose as a supporting argument for divestment, the condemnation of stocks to "sin" does not guarantee that investors will divest. On top of that, if more and more companies become listed as "sin companies," it also makes it more difficult for investors to avoid sin stocks completely.

All in all, the urge from climate negotiations motivates governments to put some pressure on the existing fossil fuel market in order to adhere to, at least in principle, the maximum of 2°C rise in global temperature. These pressures have caused fossil fuels to become more expensive, and consequently the carbon reserves, with a growing economic risk, to be potentially regarded as "stranded assets." From a moral perspective, climate change can lead to overwhelming detriment to the well-being of human life, and thus the stocks associated with the promotion of climate change (fossil fuels) can be condemned as "sin stocks," as in the case of tobacco, alcohol and gambling industry.

4 Introducing the MLP Model

The multi-level perspective (MLP) model is a framework that has been used to understand changes in sustainable innovations and transitions to low-carbon societies, among other transitional phenomena such as the adoption of certain types of technology. MLP understands change as outcomes of alignments between developments in three different levels: niche innovations, socio-technical regimes, and socio-technical landscapes. In our study, we introduce the MLP model with the aim of using it as a backdrop to explain some of our findings regarding fossil fuel divestment.

According to the MLP model, niche innovations form outside of the core of the socio-technological regime and are usually small in size. The term "niche innovations" usually describes the initial few developments of a new method, process, or way of thinking that are somewhat marginalized (irrespective of their innate credibility) because of the existing prevalent norms. The "socio-technical regimes" are an extended version of technological regimes. Instead of merely the engineering community, this term involves scientists, policymakers, end users, and special-interest groups, all of which contribute to the patterning of technological development. The regime forms the mainstream or the aforementioned prevalent norm. It is large in size and stable, and its connection with the niches is relatively unstable. A level above the rest, the "socio-technical landscape" consists of, among others, macroeconomics, deep cultural patterns, and macro-political developments. The landscape forms an exogenous environment where the regime and niche actors place no direct influence on it. However, it is also provides a framework to enable actors to act and react, imposing rules and parameters upon these activities. In the sense of fossil fuel divestment, one may regard the global political framework or climate change relations to be the landscape within which other forces interact. This is not to say that the landscape is concrete, and thus it is also possible that the landscape may be altered due to the forces of the other levels. The actors could still influence the landscape through their actions indirectly, although slowly [19]. As illustrated in Figure 1, both landscape changes and niche innovations can affect the regime. Landscape changes may impose external pressure for the regime to change. In the recent world, examples of external pressures include population growth, urbanization, and epidemic disease outbreaks, among others.

From the bottom up, niche innovations can put pressure on the regimes as they develop and grow. They may also fuse into the existing regime, or, if conditions are favourable, even break apart or disrupt the existing regime. Timing is a crucial issue: The effects of landscape pressures affecting the regime depend on whether the niche innovations are respectively well developed or still in their early phases [19]. This may offer some hints on how timing may play a role in the fossil fuel divestment scene, and how the maturity of fossil-free mentalities or activities may affect its developmental trajectory. Niche innovations and their disruptive potential have received much interest from scholars and policymakers. It has also been noted, though, that the destabilization and decline of existing regimes may be worth more investigation if a better understanding of regime changes and transitions is sought [20].

In this study the MLP model is used to illustrate how different actors in the divestment debate interact and relate to one another, amidst the changing, possibly volatile, pressures that shape the different perceptions of divestment feasibility and performance. Regarding fossil fuel divestment, it is clear that the "landscape pressure" hangs delicately upon the commitment of governments and their willingness to adhere to climate change or carbon emission targets. These commitments allow for governments to create policies and mandates, which are the primary determinants for the financial and economic viability of renewable sources at large and, of course, divestment from fossil fuels.

The current financial regime is heavily invested in the use of fossil fuels. It is also influenced by the climate change negotiations (landscape change) and divestment decisions of investors trying to avoid the carbon bubble and campaigners of divestment movement calling for carbon-free investments (niche innovations). It is a core question whether divestment from fossil fuels (helped by the pressures of climate change negotiations) can destabilize or change the regime. We shall revisit these discussions toward the end of the discussion.

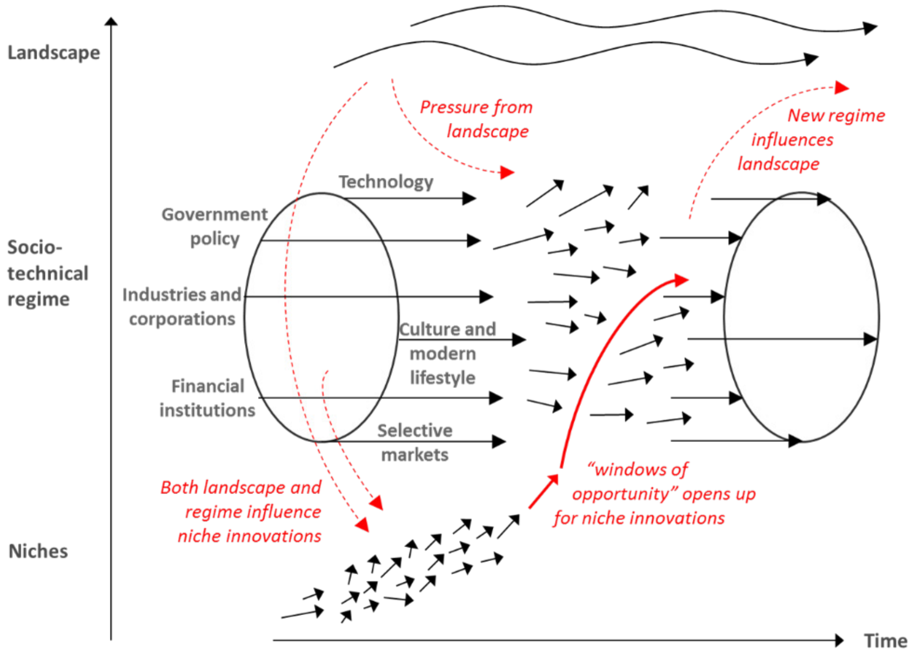

Figure 1. ***Multi-level perspectives on transitions (adapted from [19]).***

5 *Analogies from Tobacco and Apartheid Divestment*

Learning from the past has the advantage of drawing out the parallels and plausible trajectories the fossil fuel divestment campaign could take based on the evolution and outcomes observed in comparable previous campaigns. By observing the mechanisms and direct and indirect impacts of previous campaigns on target firms, we can form evidence-based judgments about the more likely paths and outcomes of the fossil fuel divestment campaign [16]. We have thus chosen to study two recent campaigns considered to be divestment campaigns—the tobacco industry and apartheid in South Africa—in order to extract some empirical causalities, allowing us to draw a comparison with the campaign for divestment from fossil fuels. That said, there are several differences among divestment campaigns that limit their comparability. For instance, a majority of the outflows related to the South African apartheid campaign are defined as disinvestment as opposed to divestment because they were linked to private corporate disinvestment of physical assets held in South Africa [21]. On the other hand, the fossil fuel campaign is unlikely to trigger voluntary corporate disinvestment solely based on social or ethical responsibility. Furthermore, the market capital of targeted firms in the divestment campaign can vary greatly. All things considered, however, the limitations are not completely grave. Despite the small size and limited data availability for some of the campaigns (e.g., alcohol and biotech/animal testing divestment), others such as tobacco are more widely documented. Moreover, several of the divestment categories of stock are collectively called "sin stocks." Knowledge about outflows in one sin industry such as tobacco allows for more general inference of patterns about other sin stocks because investors who divest from alcohol or defence stocks generally also divest from tobacco and gaming.

5.1 Tobacco Campaign

Since 1990, the movement to divest stock holdings in the tobacco industry has gained momentum in the United States. Although many organizations have always refused to hold shares in tobacco, because of their religious or moral beliefs, wide-ranging companies and organizations are now divesting in the name of social responsibility. Investors and trustees have grown increasingly aware of the negative health impacts of cigarettes and of the youth marketing practices used by the tobacco industry. Consequently, many chose to divest, despite the fact that tobacco stocks have traditionally been quite lucrative. With litigation against the tobacco industry growing, many stakeholders now see financial reasons for divestment. A report by the Investor Responsibility Resource Centre (IRRC) in January 2000 presents a comprehensive review of the history of tobacco divestment and the implications, both positive and negative, for stakeholders who choose to divest [22].

In choosing whether or not to divest in a company for reasons of social responsibility, several considerations must be made. First, is it more effective to divest or to continue holding shares, thereby maintaining a voice in the company? Between 1990 and 2000, shareholders have proposed more than 100 resolutions concerning the business practices of tobacco companies, yet none of these has been accepted. Second, many trustees have a legal obligation not to take any action that may result in financial loss to the company. For instance, Philip Morris (American Tobacco Company) was broadly considered one of the most successful stocks in the United States. As a result, many investors did not feel they could sell Philip Morris stocks and still maintain their financial obligation [22]. However, it was also analytically shown that tobacco-free funds are at least as profitable as portfolios including tobacco, if not more so. Such information imposes great motivation for trustees to divest.

Tobacco divestiture development can be historically described in four distinct phases. The first phase of divestment began in the 1980s among public health organizations, including the American Public Health Association, the American Cancer Society, and the World Health Organization. These organizations found tobacco to be contradictory to their missions and thus an unacceptable investment. During the 1990s, a second phase emerged when several major universities with strong affiliations in medical and science fields also decided to divest. The first of these were Harvard University and City University of New York. Johns Hopkins University followed shortly thereafter, then several leading health-care providers and health insurance agencies also divested.

The third phase of tobacco divestment began in the 1990s when several public pension funds began to divest tobacco holdings. This was due in part to the 1994 decision by the U.S. Food and Drug Administration to push toward regulation of the tobacco industry. Increased regulation, which could cause financial burden on the industry, was of grave concern to the investors. At the same time in Mississippi, Mike Moore, the state attorney general, filed a suit against the tobacco industry to retrieve medical aid funds for tobacco-related illness caused in the state. This suit was the forerunner to the collective suit that was filed by 46 states and resulted in the Master Settlement Agreement. In 1996, as state pension funds began to reconsider the financial strength of tobacco stocks, several decided to divest or discontinue further investment in the industry. In 1997, Massachusetts enacted legislation that required the state pension fund to sell tobacco stocks within 3 years, but also barred all future investments in tobacco. In 2000, Phil Angelides, state treasurer of California, placed a suspension on tobacco investment, and encouraged other leading public employee pension funds (e.g., State Teachers Retirement System and California Public Employees Retirement System) to divest their tobacco holdings. The fourth and latest phase of the divestment takes the form of the Master Settlement Agreement debate. As the compensation funds from tobacco companies are paid, many states are considering investing these funds for future use. Ironically, this means that in some cases settlement funds are being reinvested back into the tobacco industry. It is still unclear how most states and local governments are using their share of settlement funds [23]. The debates continue on state and corporate levels, and many tobacco-free funds are still offered by major investment firms.

5.2 Apartheid

Inspiration for the fossil fuel divestment idea leans heavily on the perceived success of the South African divestment campaign in the 1980s in putting pressure on the South African government to end apartheid [16]. Already by the early 1970s an awareness of apartheid began to develop outside South Africa. Five major Protestant denominations in the United States (with 21 million members) began to exert pressure on U.S. companies operating in South Africa to improve the conditions of their black workers. In 1973, the Church of Christ proposed the first resolution, demanding better working conditions for black employees, although it garnered only 2% of the vote. In the same year, a number of banks began to restrict loans to South Africa, and some U.S. companies began to disclose their activities in South Africa. Following strikes by black miners in South Africa's largest gold mine, the United States announced in 1976 that it would begin to use political and economic leverage to counter apartheid. Racial unrest, strikes, and capital outflow in South Africa continued. In 1980, Protestant and Roman Catholic churches, as well as some universities, continued to pledge to disinvest USD 250 million from banks with ties to South Africa. Amidst the backdrop of domestic upheaval and violence—strikes, demonstrations, rioting, and arrests in

Johannesburg, Soweto, and mining towns—international exposure of South Africa grew, coinciding with a surge in shareholder and policymaker activism. For instance, the Bank of Boston and Chase Manhattan halted new loan activities, and the Harvard and Columbia University endowments sold off shares in companies with operations in South Africa [24].

The events in 1985 and 1986 culminated in the U.S. Comprehensive Anti-Apartheid Act. This constituted legislation imposing trade embargoes, currency sanctions, and lending restrictions. Perceived to be the most important, however, was the act's prohibition on new public and private loans and investments or other credits, except for educational, housing, or humanitarian purposes. Strikes continued, and U.S. and foreign corporations continued to leave South Africa. By 1988, the daily violence in South Africa finally declined. Still, the remaining U.S. firms (by then very few) with South African operations continued to leave. By 1989–1990, large nonviolent protests began to replace violent protests, the African National Congress was legalized, and Nelson Mandela was freed. Apartheid came to an end, and Britain became the first country to lift all restrictions on new investment in South Africa in February 1990. In 1994, Mandela won the first democratic, non-racial elections, and remaining international sanctions were lifted.

5.3 Reflections and Comparison to Fossil Fuel Divestment

The two cases just discussed give a glimpse of the nature and development of divestment campaigns in general. One can see that the economic, social, and political elements are quite intertwined when regarding force fields of divestment campaigns and their consequences. The examples drawn from tobacco and apartheid divestment indicate that the campaign typically evolves over several phases. The first begins with a core group of investors that attach particular moral criticisms to the target industry. Both divestment campaigns originated in the United States and initially focused on U.S.-based investors and international multilateral institutions, and both took some years to gather pace during the first phase, until universities such as Harvard, John Hopkins, and Columbia announced divestment in the second phase. Research by Teoh, Welch, and Wazzan [24] credits these prominent American universities as heralding a tipping point that paved the way for other universities, in the United States and abroad, and select public institutions such as cities also to divest. In the third phase, divestment campaign goes global and begins to target very large pension funds and markets norms, such as establishment of social responsibility investment funds. In the case of tobacco, during the mid-1990s, large U.S. public pension funds divested their holdings. Similarly, in South Africa, the initially U.S.-centric campaign attracted global firms in Europe and Japan to enhance domestic pressure.

Like previous divestment campaigns, the fossil fuel divestment campaign started in the United States and in the short term focused on U.S.-based investors. From the perspective of the three phases of divestment, the fossil fuel divestment has achieved a lot in the relatively short time since its inception in 2010. According to Ansar, Caldecott, and Tilbury [16], 6 colleges and universities have committed to divest, along with 17 cities, 2 countries, 11 religious institutions, 3 foundations, and 2 other institutions. In recent months, the fossil fuel divestment campaign has attempted to build global momentum by targeting other universities with large endowments, such as the University of Oxford and Cambridge in the United Kingdom. Despite its relatively short history, the fossil fuel campaign can be said to be entering the second phase of divestment.

It is worthy to note that in both the tobacco and apartheid campaigns, there were eventually strong political interventions that drove these movements beyond NGO campaigns. The extent of political intervention in fossil fuel divestment has not reached such an extent, making comparison difficult. However, many main reasons of the falling demand and risks associated with fossil fuels are indeed due to government mandates to encourage renewable energy use and combat climate change. A perfect example of this is the advent of renewable biofuels. There is no doubt that producing renewable biofuels is inherently much more expensive than traditional means; nevertheless, thriving new markets are making their way because of government mandates. Very similar interventions are seen in subsidies for the encouragement of solar power, which is one of the fastest growing renewables, and it could be regarded as a result of political intervention. Perhaps in the future even heavier political weight will be imposed on regulating fossil fuels, even to the level of the United Nations (UN) Security Council, as was this case in the tobacco and apartheid campaigns.

We've looked at the inspiration behind the instrument of "divestment" and explored in hindsight how two major divestment campaigns have fared in the past. Through their development stories, one may start to contemplate the force fields driving the decisions and events that have driven the process for all the different players. It's evident that neither the civil society, nor government, nor financial institutions are exclusive in contributing to divestment campaigns. Moreover, given that divestment is inherently a financial issue, it does shed light on the discussions of ethics and humanitarianism. There is always give-and-take between money and morality. What is the price to pay for honouring a humanitarian principle? Should principles be the bottom line in defining driving decisions, or should it be the analytical consequences of the decision's outcomes? For instance, there has been evidence suggesting that there is no direct influence of divestment to depress prices of sin stocks. Furthermore, Teoh et al. [24] argue that despite the publicity of boycotts in apartheid South Africa and the multitude of divesting companies, political pressure had little visible effect on the financial markets. That being said, both cases did lead to successful stigmatization of the target industry, which in turn affects mass social perceptions and behaviour. The relationship between such perceptions and the market norm is complicated and fuzzy, which poses the question: even in the case that there is no direct measurable financial impact of divestment, could it indeed have brought about the changes in the social context, so much so that the political and economic aspects become indirectly shifted?

These are some principal questions upon which to ponder, in order to formulate a more insightful opinion on the divestment of fossil fuels. In the following sections we delve into more analytical details of fossil fuel divestment in the current era.

6 Financial Implications of Fossil Fuel Divestment

Recently there has been increasing discernible change in attitudes toward addressing climate change. A combination of scientific, social, political, and technological factors has led many to believe that serious action by governments to reduce greenhouse gas emissions is now increasingly likely. Several financial analysts are warning that energy portfolios face a risk that tighter regulations on emissions of carbon dioxide, a greenhouse gas, could lower demand for fossil fuels, making these assets substantially less valuable. Some are taking a radical view and recommending complete divestment from companies holding fossil fuel assets.

6.1 Rising Risk for Fossil Fuels

After the inconclusive outcome of the Copenhagen climate negotiations in 2009, the policymaking process regarding climate change is once more speeding up. As noted in the introduction, the hopes for a global international climate agreement are raising as the Paris UNFCCC summit 2015 is getting closer. Some energy-focused analysts [25] have commented on the material risk that government actions to combat climate change could depress the valuation of fossil fuel assets. For instance, a French research house [26] estimates that the fossil fuel sector would stand to lose revenues of USD 28 trillion over the next two decades if stringent controls were placed on greenhouse gas emissions [26]. Recent research from HSBC on climate change reported that European energy companies could see their market capitalization fall 40% to 60% [14] if oil prices for producers were to drop to USD 50/barrel, while the value of the coal reserve assets of four of the largest mining companies could be halved, removing USD 20 billion of value [27].

The risk is thus significant. This has been also highlighted in the Bank of England's Financial Stability Report 2012, which recognized climate change as a potential systemic risk [28]. The report included a Systemic Risk survey alerting of the need to protect and enhance the resilience of the U.K. financial system.

Many universities and foundations, such as Stanford University and the World Council of Churches, have already announced their intention to divest from fossil fuel companies [29, 30]. Although these announcements have generated a good deal of publicity, the wider investment community remains sceptical of the merits of the divestment case.

6.2 Investment Implications of Fossil Fuel Divestment

Impax Asset Management, in a recent report, investigated how three investment portfolios without exposure to the fossil fuel extraction and production sector would have actually performed in recent years. The investigation was done using the MSCI World Index as reference. The MSCI World Index captures large and mid-cap representation across 23 developed market (DM) countries and constituting 1,634 world stocks, and is used commonly as a benchmark for "world" or "global" stock funds. The study compared the performance of the following scenarios over the past 6 years:

1. The MSCI World Index
2. The MSCI World Index without the fossil fuel energy sector ("Fossil-Free Portfolio")
3. Replacing the fossil fuel stocks of the MSCI Index with a passive allocation to investible renewable energy and energy efficiency stocks (the "Fossil-Free Plus Alternative Energy [Passive] Portfolio")
4. Replacing the fossil fuel stocks of the MSCI World Index with an actively managed portfolio of renewable energy and energy efficiency stocks (the "Fossil-Free Plus Alternative Energy [Active] Portfolio")

The returns over 6 years are shown in Table 1 and Figures 2 and 3. The results show that all three alternative portfolios would have improved returns relative to the MSCI World Index, with limited tracking error. In finances, the tracking error is the divergence between the price behaviour of an investment portfolio and the price behaviour of the benchmark. The tracking error is in the context of a fund that did not work as effectively as intended, creating an unexpected profit or loss instead. The tracking error is measured as the standard deviation of the difference between the portfolio and index returns. Thus the measure reports the difference between the return the investor receives and that of the benchmark he or she was attempting to imitate.

The information ratio is the ratio of portfolio returns above the returns of a benchmark. The information ratio measures a portfolio manager's ability to generate excess returns relative to a benchmark, but also attempts to identify the consistency of the investor. This ratio will identify if a manager has beaten the benchmark by a lot in a few months or a little every month. The higher the information ratio, the more consistent a manager is, and consistency is an ideal trait in investment.

Table 1. ***Indicators over 6 years for MSCI and Fossil-Free Portfolios [25].***

Investment	Annualised Return	Annualised Volatility	Information Ratio	Tracking Error
MSCI World Index	4.1%	19.2%	-	-
Fossil-Free Portfolio	4.5%	19.3%	0.2%	1.5%
Fossil-Free Plus Alternative Energy [Passive] Portfolio	4.3%	19.8%	0.1%	1.7%
Fossil-Free Plus Alternative Energy [Active] Portfolio	4.5%	20.0%	0.2%	1.9%

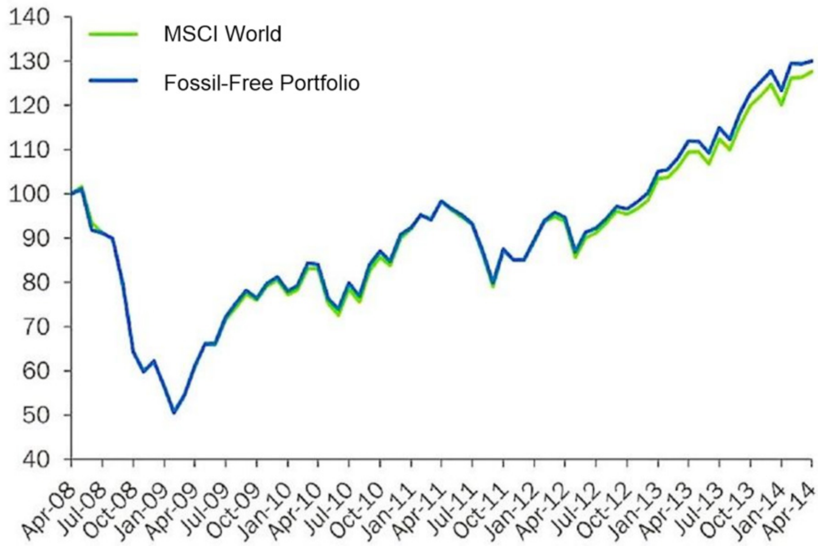

Figure 2. ***Return on investment over 6 years, comparing the MSCI and the MSCI without fossil fuels. Source [25]***

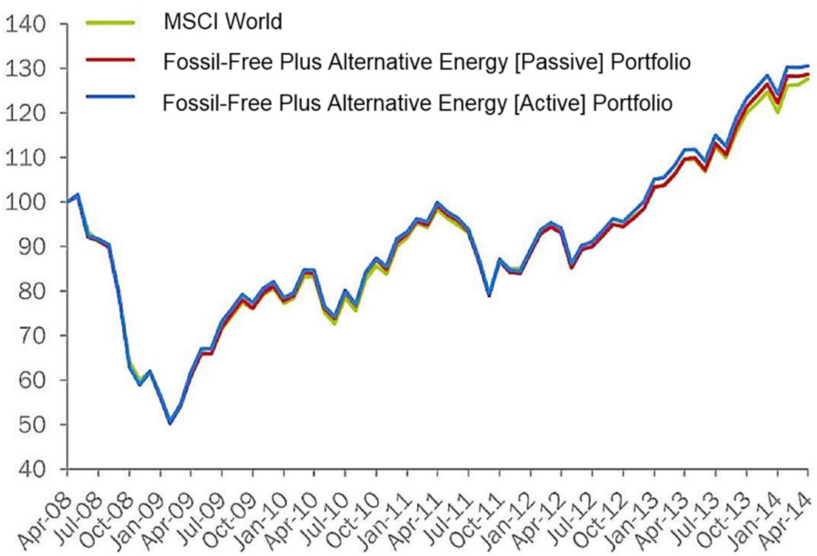

Figure 3. ***Return on investment over 6 years, comparing the MSCI, the Passive Fossil-Free portfolio, and the Active Fossil-Free portfolio [25].***

The fossil fuel energy stocks are first removed from the MSCI World Index. To give an idea, the top 10 fossil fuel energy constituents of the MSCI World Index are shown in Table 2.

Table 2. ***Current top 10 fossil fuel energy constituents of the MSCI [25].***

Company	Weight in Sector	Sub-industry	Region
Exxon Mobil Corporation	13.8%	Integrated Oil and Gas	North America
Chevron Corporation	7.5%	Integrated Oil and Gas	North America
BP PLC	4.9%	Integrated Oil and Gas	Europe
Royal Dutch Shell plc Class A	4.7%	Integrated Oil and Gas	Europe
Total SA	4.7%	Integrated Oil and Gas	Europe
Schlumberger NV	4.1%	Oil and Gas Exploration and Production	North America
Royal Dutch Shell plc Class B	3.3%	Integrated Oil and Gas	Europe
ConocoPhilips	2.7%	Oil and Gas Exploration and Production	North America
Occidental Petroleum Corporation	2.4%	Integrated Oil and Gas	North America
BG Group plc	2.1%	Oil and Gas Exploration and Production	Europe

Excluding the fossil energy stocks from the MSCI World Index (Table 1) over the last 6 years to the end of April 2014 would have improved returns by 0.4% annually, to 4.5% a year from 4.1%. The tracking error was 1.5% and the information ratio was 0.2. This result mirrors recent research carried out by MSCI that has analysed the impact of removing 76 oil and gas exploration companies and 14 coal and consumable fuels stocks from its All-Country World Index (ACWI) Investable Market Index. The test analysed data between January 2007 and December 2013 and shows that the MSCI ACWI Index, with the fossil fuel constituents removed, outperformed by an annualized 0.1% of returns with a tracking error of 1.2% [31].

Aperio Group has also examined the effects of removing the oil, gas, and consumable fuels sector from the MSCI ACWI Index and then optimizing the hypothetical portfolio to track the original index as tightly as possible. Over a 14-year period ending on December 31, 2013, Aperio found that this increased annual returns by 0.34% while generating a small tracking error of 0.8 [32].

Despite these encouraging historical data, investors may be understandably concerned that excluding an entire sector such as fossil fuel energy may result in missing out on any future outperformance of the energy sector. It is thus natural to gauge the reinvestment of divested funds. As a replacement for MSCI Energy, the MSCI World Index fossil energy sector is replaced with the Environmental Opportunities (EO) Energy universe of the Financial Times Stock Exchange (FTSE) and analysed. The FTSE EO Energy universe currently comprises 247 energy efficiency and renewable energy stocks. Over the 6 years to April 2014, the portfolio would have outperformed the MSCI World Index (Table 1, Figure 3) by 0.2% per year with a tracking error of 1.7%, producing an information ratio of 0.1.

Since 2008 Impax has been actively selecting and weighing stocks from the FTSE EO Energy universe. This enhanced energy strategy was managed defensively during the recent recession. Over the 6 years to April 2014, analysing the portfolio where fossil fuel stocks are replaced with the Impax enhanced EO energy strategy, it would have delivered an annual return of 4.5% [25], as shown in Table 1. This is an even higher return than the fossil-fuel-free MSCI World Index, as well as the case where MSCI World Index fossil fuel energy is merely replaced with the FTSE EO Energy universe.

Such analyses show the financial feasibility and actual favourability of divestment from fossil fuel stocks, which has often been considered an outlandish notion. Although divestment does not cover the reinvestment of the divested funds, the analysis that considers the two reinvestment cases in renewable energy funds shows even better returns over the 6 years of the analysis period. This is a motivating point for investors to reinvest their divested funds into renewable energy funds, even if it's solely on a financial basis.

In the next section, we focus our attention on Nordea Bank AB (commonly referred to as Nordea) for an in-depth investigation on Nordea's attitudes regarding fossil fuel divestment and the considerations taken from the perspectives of a financial institution.

7 Investigation and Field Work on Nordea Bank

7.1 Short Intro/Motivation

Nordea Bank AB, commonly known as Nordea, is a Nordic-based financial services group operating in Northern Europe. The bank is the result of the successive merger and acquisitions of the Finnish, Danish, Norwegian, and Swedish banks of Merita Bank, UniBank, Kreditkassen, and Nordbanken that took place between 1997 and 2000. Nordea is headquartered in Stockholm and has more than 1,400 branches. The bank is present in 19 countries around the world, operating through full-service branches, subsidiaries, and representative offices. Nordea currently serves 11 million private and 700,000 active corporate customers. The group also operates an Internet bank, which has more than 5.9 million online customers sending more than 260 million payments per year.

Given the scale of Nordea as a massive conglomerate financial institution, it is a natural subject of investigation regarding the issues of fossil fuel divestment. Furthermore, our team was able to reach an internal contact at Nordea—Mr. Antti Savilaakso, Director of Responsible Investments and Governance—who was kind enough to provide insightful perspectives on Nordea's fossil fuel divestment agenda and elaborate on responsible investment in the broader sense.

Antti Savilaakso, Director of Responsible Investments and Governance, is in charge of responsible investments at Nordea Bank (Nordea). As the title suggests, his scope of work goes beyond traditional financial analysis and also takes into account the global consensus of the 2°C target in Nordea's agenda. Traditionally it has indeed been popular belief that a responsible investment is inversely proportional to profitability. However, this investigation into Nordea's perspective reveals new sentiments on the relationship between responsible investments and financial returns, and how that ties in with the divestment of fossil fuels at large. The following discussions shed some light on how Nordea justifies the economic aspect of responsible investment, fossil fuel divestment.

7.2 Points/Findings Extracted from the Nordea Study

To offer a broader perspective, the total market capitalization of fossil fuels amounted to USD 64 trillion in 2013. In the United States, investments in fossil fuel energy was USD 1 trillion, and for renewable energy, including low-carbon-generation energy and energy efficiency, was USD 0.41 trillion [1].

According to the news published on January 28, 2015, by Yle News, Nordea Bank announced the removal of up to 40 mining companies from its funds. These companies' value amounted to a total of 100 million euros, although it is of a minimal percentage compared to the fossil fuel energy investment in 2013 (USD 1 trillion). Nevertheless, as the news article suggested, this implies a strong message for other asset managers to follow suit. The divestment plans in 2015 by other financial institutions included Andra AP Fund of Sweden, which will sell off its investments of 90 million euro in the coal, oil, and gas industry, and KLP of Norway, which will invest 57 million euros more in renewable energy while concurrently divesting [33].

According to Savilaakso, the decision to remove the 40 mining companies was based on economic justifications from the company's extensive climate-related financial research (conducted by ESG Nordea), underpinned by environmental and social governance (ESG) principles. In addition, other experts on climate-related financial analysis, for example, the research of Carbon Tracker Initiative, act as supporting guidelines for Nordea. The economic motivation includes the dwindling in coal prices and demand, and the risks of stranded assets and the carbon bubble. These drove Nordea to reconsider its loan plans to the high-carbon corporations. Despite the removal of 40 mining companies, however, Savilaakso emphasized that divestment indeed accounts for a small portion in the global fossil fuel funds, which amounts to a total of USD 1 trillion. This figure is insignificant in meeting the global target of 2°C rise. Therefore, there are other tools with which Nordea leverages its resources under its "climate umbrella," including Engagement, Star Funds, and other policy-related initiatives, such as providing recommendations for the Institutional Investors Group on Climate Change (IGCC) for enhancing collective policymaking associated with climate change on the international level, and carbon footprint tracking of Nordea funds.

We also looked at the fund sizes of the financial institutions so as to grasp an idea of the portion of renewable energy funds compared to the total funds managed. Nordea manages a totality of EUR 150 billion in funds, of which EUR 2 billion consists of renewable energy funds (1.33% of the total funds managed). According to Antti Savilaakso, the Norway State Pension Fund is the largest institution fund in Europe, having a fund size of about EUR 600 billion. Nordea Bank, with EUR 150 billion, is considered medium sized. Nordea's EUR 2 billion in renewable funds would make about 0.5% of the global USD 250 billion investment in renewable energy as estimated by the IEA. Hence, there is still much space for Nordea to expand its renewable energy investment if it is legitimated by the international climate negotiations, in sight for the 2°C target. In addition, whereas Nordea is only medium sized, there could be a big impact if the larger institutions like the Norway State Pension Fund would make a move toward fossil fuel divestment.

Underpinning Nordea's conviction to divest from fossil fuels lies the fundamental belief of responsible investments. Savilaakso elaborated on the nature and development of responsible investments. Initially in the 1970s, responsible investment activities were pursued purely for ethical reasons. As market sizes grew over time into the 1990s, corporate social responsibility became a known consideration among industries. However, responsible investments were made mainly on the basis of organizational reputation amidst the public. Today, a decade into the new millennium, things are looking rather different. Contrary to popular belief that responsible investments are purely for ethical and symbolic institutions at the cost of profitability, such investments have indeed been shown to offer long-term improvements on returns and risks. This realization seems to be spreading among financial institutions. Nordea has certainly made a commitment to support responsible investment and practices what it preaches. This creates an interesting situation in which an opportunity arises for traditionally morally motivated groups, such as NGOs and activists, and the money-driven financial institutions to see eye to eye on investment decisions.

What is also significant, according to Savilaakso, is the client demand for renewable-energy-related funds. As Savilaakso expressed, "demand represents the client need. We have to be responsible to our clients in investing with their money; we need to listen to our clients and work for the best interest for them." Savilaakso continued, "From my asset management viewpoint, the client's decision on engaging in renewable-energy-related funds is 30% reasoned on monetary return while the bigger portion of 70% is on their moral belief for environmental goods." He concludes, "It's the ethical decision that transforms into economic justification which reasons banks to provide tools to realize our clients' values" [2]. At the same time, the economic justification from the bank confirms the clients' moral decision, and hence attaches a meaning to the renewable-energy-related engagement. As can be expected, personal clients, being human after all, demand a certain moral standard, despite the desire for high returns. Indeed, clients are important drivers too for the direction of banks' investments. Even the change in social norm alone could displace the stance of financial institutions should they wish to honour the voices of their clients. This once again highlights the complex interplay between social perception and financial value, underpinning the dynamic interactions between different players within society.

8 Social Movement for Divestment

Returning to our historical study on the campaigns of tobacco and apartheid in South Africa, it is obvious that social movements and public opinion had a clear influence on starting the divestment movements and carrying them forward. Moral arguments were behind many of those organizations that refused to hold shares in tobacco companies or divested from South Africa during its apartheid period. This mechanism is definitely at work in fossil fuel divestment and is encouraged by civil society movements.

The first steps for the fossil fuel divestment campaign were taken in 2010 at Swarthmore College, where students pledged to the college endowment fund to sell all shares of fossil fuel companies. The pledge was inspired by a student's trip to West Virginia, where coal mining from a mountaintop was causing landscape destruction and poisoning of the Appalachian communities. The students decided to campaign against the coal-extracting companies by targeting their financing: by demanding divestment from fossil fuels, starting with their own university [34].

The divestment campaign spread through the United States after *Rolling Stone* magazine published an article by Bill McKibben titled "Global Warming's Terrifying New Math" on July 19, 2012. Calling for a fossil fuel divestment campaign, McKibben [35] explained that in order to have an 80% chance of keeping global warming below 2; , only 565 Gt of CO_2 can be emitted between 2010 and 2050. By contrast, burning all the currently proven oil, gas, and coal reserves of fossil fuel companies would release 2,795 Gt of CO_2 into the atmosphere. This is almost five times the "carbon budget" of 565 Gt CO_2 [35]. In November 2012, McKibben and 350.org [36] started a road-trip campaign to build the fossil fuel divestment movement. By 2015, the U.S. campaign had encouraged 20 educational institutions, numerous cities, the counties of San Francisco and Dane County, and many other institutions to commit to divestment [37].

Although the campaign is supportive of individuals divesting their own money, the focus is decidedly on public funds and, in particular, university endowment funds and pension funds [16]. The campaign started in the United States, but has spread over continents, and currently has activity also in Canada, Europe, Australia, New Zealand, and South Africa. The two main demands of all divestment campaigns throughout the world are: "immediate freezing of any new investment in fossil fuel companies and divestment from direct ownership and any commingled funds [funds consisting of assets from several accounts that are blended together] that include fossil fuel public equities and corporate bonds within 5 years" [38]. Although the direct target of the campaign is divestment, it also aims to pressure the government to such legislative actions that would ensure that fossil fuels would be left underground. Also, it aims to put pressure on fossil fuel companies to transform themselves into supporting the transition to less-carbon-intensive forms of energy supply [16]. The campaign appeals to people's sense of justice by presenting divestment as "the right thing to do." The activists also hope that through the divestment campaign, they will be able to stigmatize the fossil fuel industry and open up space for political action on climate change [39].

In recent days, the fossil fuel divestment campaign has attempted to build global momentum by targeting other universities with large endowments, such as the Universities of Oxford and Cambridge in the United Kingdom [16]. Regulatory and policy developments are encouraging the fossil fuel divestment campaign [25]. In May 2014, Stanford University announced its intention to exclude holdings in 100 publicly traded coal-extraction businesses from its USD 19 billion endowment, and divest any direct holdings in privately held coal assets [29]. The University of Dayton, in June 2014, said it would begin to divest coal and fossil fuels from its USD 670 million investment pool [40]. Many foundations and religious institutions have also made divestment commitments, with the World Council of Churches, representing 500 million Christians, being one of the latest to do so [41].

The campaign is getting its message to wider audiences as well. Recently, it has been backed by the UN [42] and the Guardian Media Group [43]. The latter has also started its own campaign, called "Keep It Underground," which demands that the world's two biggest charitable funds should divest [44].

In Finland, the campaign has started recently and is being coordinated by the activists of 350.org. The first pledge for university endowment divestment has been made by students of University of Oulu and was followed by a pledge for the University of Helsinki. The campaign is following the example of the U.S. campaign: awareness-raising events showing the *Do the Math* movie, also serving the purpose of gathering volunteers for the campaign among the students and other interested people [36]. During the Global Divestment Day, a singing protest was also organized in Helsinki

Figure 4. ***Scene of the divestment campaign gathering in central Helsinki.***

(Figure 4). The day also involved encouraging individuals to personally inquire about fossil-free investment options at their banks.

The impact of the divestment movement is hard to measure. It is clear that it has been influential in the decisions of many institutions to divest, and it has gathered support from a wide range of societal actors. Nevertheless, some of the investment decisions might have been made even without the movement, based solely on the analysis of the future of coal and its value. This is reflected, for example, in the Nordea case, where the bank decided to divest from coal mining companies, which are not profitable in any case. Thus, in such situations, there doesn't need to be any ethical considerations, as the financial ones clearly indicate that the stocks should be dropped. The divestment movement can, however, have social and political influence, which in turn might lead to bigger divestment decisions. In the following conclusive section we will examine in more detail the overall picture and revisit some of the previously mentioned discussions.

9 Synthesis: Conceptual Frameworks of Fossil Fuel Divestment

So far we have discussed international climate negotiations and the financial and moral perspectives of fossil fuel divestment. We have also taken note of the earlier divestment campaigns and their progress. By investigating the financial aspects of divestment, we have shown that divestment from fossil fuels is indeed financially feasible, if not altogether more favourable. However, it is questionable whether the financial aspect in itself would have been sufficient to cause the social shift and political change required for a carbon-free world. Furthermore, although we have shown that the social movement has managed to pressure especially educational institutions to divest from fossil fuels, it is obvious that without the supporting financial arguments, the movement will not be able to reach the bigger players. Thus, in the case of fossil fuel divestment, an interesting result is revealed, that neither NGOs (representing social/moral motivations) nor the financial institutions (representing financial motivations) can single-handedly lead the way toward a fossil-fuel-free society.

To shed light on divestment theoretically, we revisit the MLP (multi-level perspective) model introduced earlier. It can be shown that both "morality" and "money" are crucial actors in fossil fuel divestment, and of which the interaction is contributing to transformation of the regime. Figure 5 illustrates these interactions, as witnessed in our case studies of the Nordea Bank and the divestment campaign. In these cases, individual motivations to combat climate change transform into collective action, organized through campaigns to demand divestment from fossil fuels. Individual investors then transform these ethical decisions to justify their economic goals. The cluster of grey arrows in Figure 5 symbolizes their desires and motivations. The red arrow illustrates how the ethical decisions of these investors are transformed into economic justifications through the banks' willingness to respond to their needs by providing tools to realize these anticipations. The financial institutions thus need to take into account both customer needs and the surrounding economic and political environment. In the Nordea case, the bank recognized the "dispersed" individual client need as a signal of significant "escalating demand." Clearly, the bank has been monitoring the situation for some time. However, one clear signal from the customers was given on the Global Divestment Day, when 30 to 50 clients knocked on the door of Nordea to inquire about solutions of renewable-energy-related funds. The number of people requesting Nordea for the same investment solution on one single day caused significant pressure, which the bank could not ignore. It's worthy to note also that this body of clients consisted of actors who were mobilized by an NGO. From this incident, Savilaakso recognized the role of NGOs in encouraging action and acknowledged that the banks regard their clients' demands with high priority [45].

The globe in Figure 5 represents the organizational field inside the fossil fuel regime—a term borrowed from Geels and Schot's MLP model [19]. The key players identified include the government, corporations (private sector, fossil fuel companies, coal power plants, automobile and construction industries, etc.), and financial institutions (banks and their financial analysis units, fossil fuel capitalization market, etc.). The key players interact with each other, as symbolized by the two-ended arrows in Figure 5, both reinforcing the activities of each other and exerting pressure on others internally within the field. For example, Nordea Bank's divestment news has placed pressure for the possibility to decline the financing of loans to fossil-fuel-related companies if they do not improve their energy technology and investment plans.

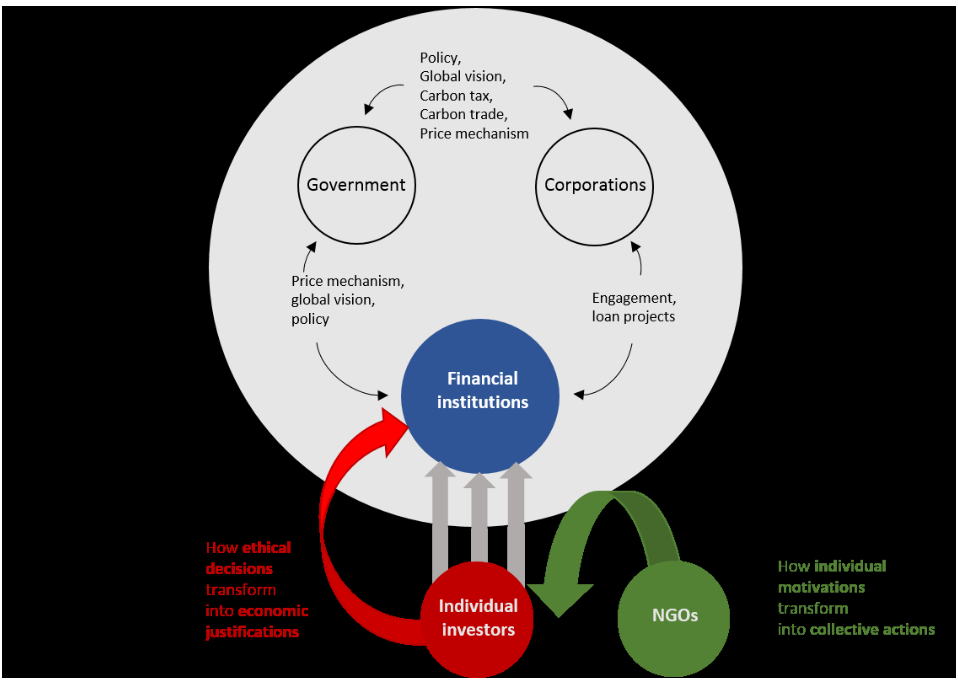

Figure. 5. Illustration of the transformation of decisions and motivations into justifications for actions.

To gauge the current state of the fossil fuel divestment path, a broader perspective can be taken. It is clear that the size of the campaign is favourable on the side of the regime: As highlighted by Ansar [16], fossil fuel and related industries comprise a surprisingly large variety of sectors, from coal mining to shipping to the manufacture of premium steel. The key field players could be the high-carbon industries and corporations, for example, coal power plants, automobile and construction industries, financial institutions and their financial analysis units, the fossil fuel capitalization market, price mechanisms yet lacking externalities, technologies enhancing the extraction of oil, policies, deep cultural patterns, and modern lifestyle including transportation, heating, and air conditioning. The regime is illustrated by the big arrow in Figure 6. That said, there are already niches emerging that challenge the mainstream regime: the campaign activists (Global Divestment Day, when 30–40 people went to Nordea) on fossil fuel divestment, economic research institutes like the Carbon Tracker Institute, outside scientific proof by outside scientists and analysts, financial actors developing fossil-free indexes, renewable energy technologies and innovations, and so forth.

On the one hand, banks on the regime level are reacting to the "landscape pressure," by which we mean the climate change negotiations aiming for the 2°C target. At the same time, on the niche level, the outside expert Carbon Tracker Initiative acts as one of the various niches at the fringe of the regime in our conceptual landscape model yet further economically justifies Nordea through scientific motivations. Likewise, Nordea's announcement of its divestment plan also put pressure on the fossil companies of its portfolio regarding debt financing. Furthermore, on the niche level, the individual

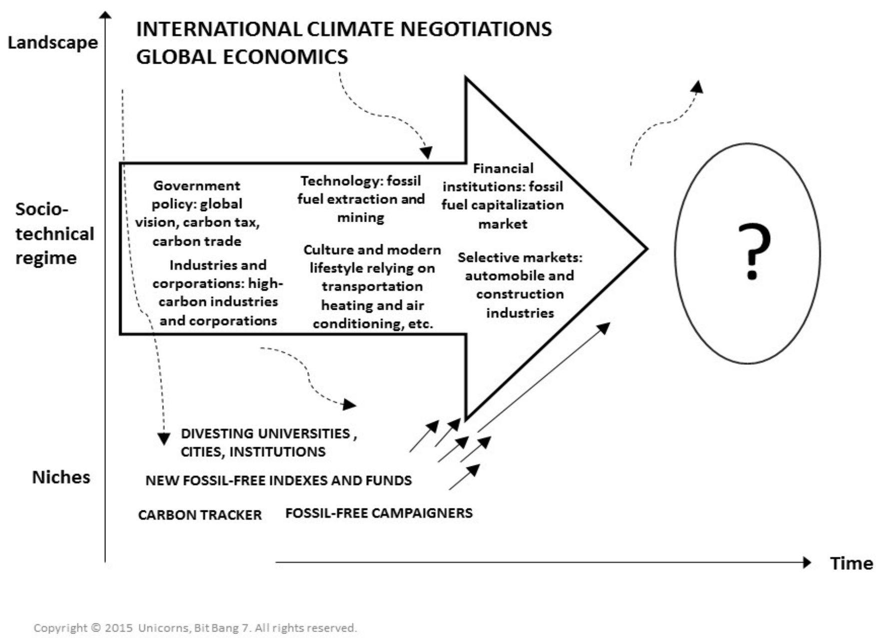

Figure 6. ***Multi-level perspective model for fossil fuel divestment.***

personal investors also form a force when their faith in environmental goods moves to actions of demand. Furthermore, the intended mobilization power of the NGOs added pressure to the bank, which could not be ignored. However, without the external pressure from the international climate change negotiations, it is difficult for the niches to replace or change the regime. The external pressure opens the "windows of opportunity" [19] for the niches to break into the mainstream, if the niches could make use of the windows by providing ready niche innovations. It is the variation of timing, as mentioned earlier, that affects the development of the transition pathway.

In this section, we have illustrated the current situation of the fossil fuel divestment in the multi-level perspective. We have shown how the mainstream regime, niches, and landscape are positioned and how they interact. From these premises we will move on to discuss the possible consequences of the fossil fuel divestment and present our scenario in which the divestment from fossil fuels has led to a system change.

10 Discussion and Future Scenario: Toward High Awareness in Both Money and Morality

Our societies are still built upon high-carbon solutions, and the real coal price does not reflect its true costs to people and environment. Thus the fossil-fuel-based market is still a mainstream, allowing the fossil fuel socio-technical regime to stay quite stable and continue its existing trajectory. Economic and technological interactions by the regime field players reinforce the regime and stabilize its path. However, as described in this article, this state of affairs is under debate. The divestment campaigners are pushing for investors to give up on their fossil fuel funds, and the financial institutions are starting to realize that these funds bear a financial risk. The question here is whether these activities, backed up by the external pressure to mitigate climate change, will in fact have a transformative effect. Nevertheless, elements driving fossil fuel divestment have been identified in this study, and thus more educated guesses can be made regarding a future scenario. In this section we present a model of the potential scenarios of divestment based on the nature of the mentality norm. In the same way that tobacco and apartheid have become condemned, just as countless practices throughout history (e.g., slavery), so could fossil fuel and climate change undergo more widespread stigmatization. The concept of responsible investments is becoming a norm, especially as it goes hand in hand with long-term financial stability and lower risks. Aside from large corporations and financial institutions, the demands of personal investors also play a significant role. As illustrated in the previous section (MLP model on fossil fuel regime), the change is dependent on interactions between actors at different levels and the possibility that political, social, and economic change can reinforce the financial message to the investors. We construct a scenario model (Figure 7) to describe possible trajectories of fossil fuel divestment with respect to the balances of different schools of thought amidst all players. We then propose the favourable future scenario and explain the reasoning. We base our scenario on the interplay between the two principal components of divestment mentalities: the levels of "moral awareness" and "money awareness" (Figure 7). This is shown as the two main dimensions of the scenario diagram. In our view, another crucial element affecting the future path is timing—whether the niches can break into the mainstream is dependent on whether the pressures coming from the international negotiations and the niches impact the regime simultaneously or not. The different variations of the timing of this interaction form the core of the four quadrants underpinned by the two major axes (Moral Awareness and Money Awareness) in our scenario.

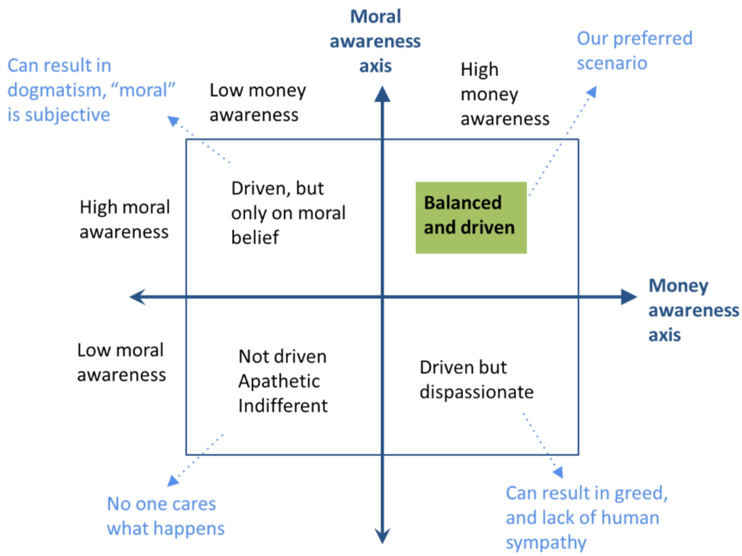

Figure.7. ***Scenario model.***

Each of the four quadrants presents a certain profile of perception or mentality by different actors at different times of the development path of divestment movements. The following sections elaborate on each profile, and examples are given to illustrate their relevance.

10.1 Low Money, High Moral Awareness

The top left quadrant describes the mentality where there is greater focus on ethics and morals. In this quadrant, all of the financial decisions are based upon principles and values. Interestingly, as discussed in the case of the apartheid and tobacco divestment campaigns, such profiles are usually the initial drivers of divestment. These drivers consist of supposed high-morality entities such as churches, NGOs, and universities, where profitability is of lesser priority. This is thus an important stance to adopt as a normal scenario in the future. However, these drivers do not often substantially affect the society at large. Finances are more driven by economic gains. Politics, however, is influenced both by economic gains and various other values and ethical perspectives, which do not always share the same moral values as those cherished by these supposedly high-morality entities. Needless to say, countless ethically driven campaigns have emerged and faded away. Still, as in the case of tobacco and apartheid, these divestment campaigns are considered as successes, because of the way they affected social perceptions, so much so that the other aspects are affected too. As the fossil fuel divestment campaign already has some social impact and publicity, it could encourage social perceptions concerning climate change issues. Thus high moral awareness is particularly important for societal change to take place. That said, there is a danger of dogmatism and economic chaos in this scenario. First, greatly emphasizing only the use of fossil fuels as an ethical standard can override other societal concerns, such as economic equality and dismissal of negative effects of energy based on renewable sources. Second, this option might bear seeds for chaos: should the carbon bubble burst without any precautions taken in the market sector, the consequences might be chaotic and have detrimental effects on the whole-world economy.

10.2 High Money, Low Moral Awareness

Almost as an antithesis to the previous profile, this one has high awareness of the money aspect with little regard for ethics and humanitarianism. As negative as it may appear, this is often the reality of modern life. In this quadrant, the change is mainly driven by market forces. Constituents of this quadrant are typically seen as the profit-driven corporations and financial institutions, where the main goal is maximizing financial utility despite the social or environmental costs. Indeed, this may be the reason why ethically driven entities (e.g., NGOs) are forever in conflict with the money-driven entities (e.g., corporations). In recent years, many campaigns steered by NGOs have already emphasized the economic aspects, and demands for action have been justified through financial views. In this scenario, this trend would be strengthened and ethics would only be influential when in line with financial gains.

It is often presented that if market actors are left to act freely, the markets will by themselves solve problems. Indeed, positive outcomes may well arise, assuming that the increasing financial awareness of the carbon bubble or of the better profitability of fossil-free funds will impose a change in the market norm and leave fossil fuel investments as second-class stocks/funds. The change would thus be mostly driven by investors seeking better gains provided by fossil-free investments. Taken the difficulties that the world governments are facing in negotiating rules for climate change mitigation, a change driven by financial gains might even be preferred. One cannot ignore the relevance of money in human society: There is no doubt that money is the medium by which most value is measured in our societies (and as the saying goes, "money makes the world go round"). Still, one-sided decisions totally rid of moral judgment can lead to devastating results. This can be seen in many ethically questionable practices in industry without human empathy, solely geared toward making money. In this scenario, we reserve the possibility that the carbon bubble and worst cases of climate change may indeed be successfully avoided, based solely on the increasingly favourable financial returns of fossil-free investment, as fossil fuel companies risks bankruptcy when left without financing. However, it does not guarantee any achievements in principled ethical reasoning, even in the new renewable energy markets, and could potentially give birth to other types of symptoms as a result of a lack of moral reasoning.

10.3 Low Money, Low Moral Awareness

This quadrant is just about the worst scenario. This is where society adopts a predominantly ignorant mentality, leading to broad apathy and lack of motivation and thus development. The lack of awareness both ethically and financially implies a disregard for the potential need of divestment, and thus the obliviousness to serious global warming issues. It is difficult to even imagine a future reality where this scenario thrives in society. Governments would fail miserably in negotiations of climate change, and global agreement would be left on the table; thus heavy external pressure for carbon-free investment just fades away. Civil society's efforts based on moral grounds will be futile in creating any drive, regardless of supporting or opposing divestment. It is envisioned that with this scenario, the most probable path is that the world continues repetitively, as there is no drive for development or innovation, blind to the ever-changing challenges that emerge, be it from ethical or economic perspective.

10.4 Preferred Scenario: High Money and High Moral Awareness Guiding Investments in 2030

The best scenario is one of high moral and high money awareness. This scenario takes an optimistic view of all driving forces and presents a future that could be highly desirable. In this scenario, both the financial world and the civil society have pushed for a change, resulting in balanced action. Both sides, money-driven and moral-driven, attain a state of insight upon which decisions and discussions are undertaken. Of course there are inherent traits of specific groups, but it is an ideal scenario that the general society is able to achieve a desire for objectivity and empathy toward all schools of thought. Decisions taken with this mentality may not ensure perfect outcomes—after all, one cannot predict the future—however, it is certainly the best among all of the scenarios, and the one from which the most optimal outcomes can be expected. The big question is: how could we ensure that we reach this scenario and what would the world look like then?

For this scenario to occur, the timing becomes crucial. If both the customer needs for fossil-free and renewable energy funds and the danger of the intensifying risk of the carbon bubble impose concurrent pressure on the financial sector, it will be forced to react. This scenario is based on the assumption that both financial as well as moral motivations gain more strength simultaneously. As we have seen in this article, both of these factors are already at work. There is a good chance that the UN's next climate meeting in Paris from November 30 through December 11, 2015, will attract the attention of both the financial sector as well as the civil society actors. Although the lobbying of the fossil fuel industry and its financiers will likely still aim to downplay the agreement, they only form part of the totality, many of which are supportive of fossil fuel divestment. The lobbying force of divestment campaigners can also move part of the financial institutions in favour of divestment, thus supporting the targets of the climate meeting. The interactions, though, also apply the other way around: If the financial institutions have renewable-energy-related funds available for clients, the moral arguments for divestment might be much easier to commit to. A start for these kind of funds already exists. For example, the available renewable-energy-related funds offered by Nordea, the Climate and Environment B Funds and Star Funds, amount to 2 billion euro. As mentioned previously, this only accounts for approximately 1.33% of Nordea's 150 billion euro total funds managed, but it is still a promising start. Furthermore, increasing client demand helps bring the figures up. In this ideal future scenario, all discussions made will have gone through rigorous examination and insightful scrutiny honouring both the ethical and economic interests in human society.

11 Conclusion

In this article we have investigated financial institutions and NGOs regarding their stance toward fossil fuel divestment, and we have explored the international climate change negotiations and how they create pressure for divestment. We also studied two well-known past divestment campaigns (tobacco industry and apartheid in South Africa), which have inspired the current fossil fuel divestment campaign. Finally, we drew a conceptual framework on fossil fuel divestment using the multi-level perspective.

We have shown that divestment from fossil fuels is indeed financially feasible. Moreover, fossil-free investments can actually be even more profitable than alternatives. However, it is unlikely that such divestment would progress without the NGO's campaign, which has already raised the issue in public debates and created pressure for various institutional investors to divest.

The core lesson percolated and reiterated within this study is that the values of human morality and monetary implications are not mutually exclusive, and, in fact, both are just as significant in the discussions regarding fossil fuel divestment. The preconceived belief that money and morality constitute a zero-sum game is obsolete and not completely accurate; thus, a trade-off is not always a necessity in terms of investment. Indeed, both arguments go hand in hand and are essential in the progress of human development.

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Appendices

1 The Bit Bang People

FACILITATORS

ORMALA, ERKKI – Professor at the Department of Management and International Business. He has a PhD in in Engineering from Helsinki University of Technology. He is a former Vice President of Nokia Corp. Ormala has chaired the assessment of the EU R&D Framework Program and the association of the European Digital Industry, DIGITALEUROPE. He is a member of a European Commission initiated high level advisory board on the future of the European media.

NEUVO, YRJÖ – Research Programme Director. He has a PhD in Electrical Engineering from Cornell University. He is a former CTO of Nokia Corp. He has worked as a National Research Professor at Academy of Finland and a visiting professor at University of California, Santa Barbara.

KUIKKA, MERI – Social media researcher, doctoral candidate in Information Systems Science. MSc (Information Service Management) and BSc (Business Technology) from Aalto School of Business. Current research topics include social media strategy for organizational use and challenges related to social media use in organizations.

TUTORS

ASATIANI, ALEKSANDRE – Georgian, M.Sc. A PhD student at the Department of Information and Service Management, Aalto BIZ. Research topic: Cloud computing in organizations. Other interests: long distance running, football, graphic design.

HERNANDEZ ESTRADA, ALBERT – Spanish, M.Sc. A PhD student at the Department of Forest Products Technology, Aalto CHEM. Research topic: Crop fibres, their uses in composites, and how production processes affect the end fibre quality. Other interests: Hiking, cycling, travelling, cinema, especially documentaries, and more academic interests such as innovation, product design and knowledge management.

LOOGA, VILEN – Estonian, M.Sc. A PhD student at the Department of Computer Science and Engineering, Aalto SCI. Research topic: Energy-awareness in large-scale Internet of Things networks. Other interests: Climbing, oenology.

ŠĆEPANOVIĆ SANJA – Montenegrin, M.Sc. A PhD student at the Department of Computer Science and Engineering, Aalto SCI. Research topic: Social computing application to investigating human mobility and smart energy cities. Other interests: Dancing, astronomy, traveling.

ALA-MANTILA, SANNA – Finnish, M.Soc.Sc. A PhD student at the Department of Real Estate, Planning and Geoinformatics, Aalto ENG. Research topic: Sustainable built environment. Other interests: Reggaeton, drawing, literature.

CRONHJORT, YRSA – Finnish, Architect. A PhD student at the Department of Architecture, Aalto ARTS. Research topic: Implementing TES Opportunities for Building Regeneration through Retrofits with Prefabricated Timber Based Element Systems in the Finnish Context. Other interests: Long walks, gym, photography, cooking.

FRÄKI, JOHANNA - Finnish, M.Sc., MBA. A PhD student at the Department of Industrial Engineering and Management, Aalto SCI. Research topic: Commercialization of customer driven innovations. Other interests: Green energy.

GARIMELLA, KIRAN - Indian, M.Sc. A PhD student at the Department of Information and Computer Science, Aalto SCI. Research topic: Social network analysis. Other interests: cricket, debating, international news.

HOSSAIN MM AFTAB – Bangladeshi, M. Sc. A PhD student at the Department of Communications and Networking, Aalto ELEC. Research topic: Energy efficiency of wireless network.

ISLAM, MD.MAZIDUL –Bangladeshi, M.Sc. A PhD student at the Department of Radio Science and Engineering, Aalto ELEC. Research topic: Passive wireless sensors. Other interests: Cricket, sauna, swimming.

KAISJOKI-ROJAS, RAIJA – Finnish, M.Sc. (Chem.), M.Sc. (Tech). A PhD student at the Department of Civil and Environmental Engineering, Aalto ENG. Research topic: Waste management (Pharmaceutical waste in St. Petersburgh). Other interests: literature, gardening, sailing, skiing.

KHAJAVI, SIAVASH –Iranian, M.Sc. A PhD student at the Department of Industrial Engineering and Management, Aalto SCI. Research topic: The impact evaluation of additive manufacturing on supply chain management operations. Other interests: Books and sports.

KHAN, KASHIF NIZAM - Bangladeshi, M.Sc. A PhD student at the Department of Computer Science and Engineering, Aalto SCI. Research topic: Energy-efficiency in heterogeneous computing environment

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KUO, VINCENT -South African/Taiwanese, M.Sc. A PhD student at the Department of Civil and Structural Engineering, Aalto ENG. Research topic: Semantic knowledge inference from explicit design and construction data in Building Information Models. Other interests: Music, poetry, journalism, travel, languages.

LAINE, HANNU – Finnish, M.Sc. A PhD student at the Department of Micro and Nanosciences, Aalto ELEC. Research topic: Silicon Solar Cells. Other interests: Renewables, Sustainability, Energy Policy.

MOK, LUISA -Hong Kong, MA. A PhD student at the Department of Design, Aalto ARTS. Research topic: Social Innovations and Global water issue. Other interests: Cycling, trail running.

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RUOHO, MIKKO –Finnish, M.Sc. A PhD student at the Department of Micro- and Nanosciences, Aalto ELEC. Research topic: Nanostructuring of materials for more efficient energy conversion. Other interests: Hiking, bicycling and travelling.

TYNKKYNEN, PEKKA – Finnish, M.Sc. A PhD student at the Department of Architecture, Aalto ARTS. Research topic: New Domains of Materiality. Other interests: Music writing & production, sound design, visual arts, dance & performance, yoga, poetry, philosophy, history and natural sciences.

UPRETI, BIKESH RAJ – Nepalese, M.Sc. A PhD student at the Department of Information and Service Economy, Aalto BIZ. Research topic: Text mining. Other interests: Sports.

ZHANG, RUI –Chinese, M.Sc. A PhD student at the Department of Materials Science and Technology, Aalto CHEM. Research topic: Materials Science. Other interests: Tennis, badminton.

2 Bit Bang Guest Lecturers Autumn 2014–Spring 2015

Aho Esko, CEO, Verbatum

Ala-Pietilä Pekka, CEO, Blyk
"About the new challenges of technology in social and economic development?"

Heinonen Sirkka, Professor, Finland Futures Research Centre, University of Turku
"Futures Research and Homo Scenarionicus"

Hurri Pasi, CEO, BaseN

Konola Kai, EVP, Weather Business Area, Vaisala
"Vaisala- Moving into Energy"

Lindfors Lars-Peter, Senior Vice President, Technology, Neste Oil
"Neste (Oil) – Renewing itself through renewables"

Lundström Petra, Vice president, Nuclear Development, Fortum Power and Heat *"Solar Energy:Technologies, markets, CO2 emissions, impact on energy system"*

Mickwitz Per, Research Director, Finnish Environment Institute (SYKE)
"Change and Stability in Energy Systems"

Neuvo Yrjö,, Reseach Director, Aalto University
"Aalto Energy Efficiency Program"

Niemelä Marita, Vice President, Strategy, Valmet Pulp and Energy
"Introduction to Sustainable Energy"

Ojanperä Tero, Managing Partner, Vision+
"How to save the world"

Pantsar-Kallio Mari, Director, Sitra
"Towards Carbon Neutral Society"

Pesonen Jussi, President and CEO, UPM
"More with Biofore: UPM in Transformation"

Plit Herkko, Deputy Director General, Ministry of Employment and the Economy *"Finnish Energy Policy"*

Pulkkinen Tuija, Vice President. Research and Innovations, Aalto University *"Multidisciplinary Research at Aalto University"*

Savilaakso Antti, Director of Responsible Investments, Nordea
"Responsible Investments"

Soini Pekka, Director General, TEKES
"TEKES- Joy of Innovation"

Turpeinen Marko, Director, EIT ICT Labs Helsinki
"Creating ICT Innovations for Sustainability at EIT"

Virtaharju Jouni, Researcher, Aalto University
"Orientation to team work"

Wilska Kari-Pekka, Independent AdvisorResearch Centre, University of Turku *"Futures Research and Homo Scenarionicus"*

3 Course Literature

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Bit Bang 3 -Entrepreneurship and Services. Yrjö Neuvo & Sami Ylönen (eds.) 2011. Aalto University.

Bit Bang 4 -Future or Internet. Yrjö Neuvo & Elina Karvonen (eds.) 2012. Aalto University.

Bit Bang 5 - Changing Global Landscapes – Role of Policy Making and Innovation Capability. Yrjö Neuvo, Erkki Ormala & Elina Karvonen (eds.) 2013. Aalto University.

Bit Bang 6 - Future of Media. Yrjö Neuvo, Erkki Ormala & Meri Kuikka (eds.) 2014. Aalto University.

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4 *Study programme in Shanghai*

January 26th–31st 2015

Sunday January 25th , 2015

08:15 Arrival in Shanghai by AY057
10:30 Check in hotel Radisson Blu Hotel Shanghai New World
13:30- 15:30 Warm-up session: Team Finland introduction in Shanghai by Mr. Ding Ma from Consulate General of Finland, Shanghai
Finpro Shanghai presentation by Ms. Xia Li (Lisa)
17:00 Free evening

Monday January 26th 2015

08:15 Departure from hotel
09:00 Arrival in Finchi Innovation Center
09:10 Tekes presentation – Jarmo Heinonen, Head of Tekes Shanghai
09:50 Finchi presentation – Ms. Joan Zhang
Rep of Finchi Innovation Center
10:30 coffee break
10:45 Tong Ji Prof. Long WeiDing – Tong Ji Univ.
12:00 Lunch
12:30 depart to IBM Shanghai
13:00 IBM GCG University Partnership Operations, hosted by Dr. Heng Cao
(Supported by Ms. Jean Li, operation manager)
15:30 Shanghai Aalto Tongji Design Factory, contact person: Michelle Fan
18:00 Arrival at hotel

Tuesday January 27th 2015

08:30 Leave hotel/Bus transportation
10:00 Shanghai Wireless Research Center, Dr. Hu Hong Lin
12:30 Lunch
14:30 Valmet (China) Co., Ltd. Mr. Ari Niemi, Area President, China
16:00 Bus Transportation
17:30 Hotel
18:40 Bus transportation
19:30 Era show – Acrobat,

Wednesday January 28th 2015

08:00 Leave hotel/Bus transportation
10:00 Visit Oilon Ltd
11:30 Lunch
12:30 Bus transportation
13:00 Arrival at Wuxi New District: Internet of Goods
14:40 Bus transportation
15:00 Wuxi Solar Power plant
16:00 Bus transportation
19:00 Arrival at hotel

Thursday January 29th 2015

08:15 Leave hotel/Bus transportation
09:00 Arrival at Shanghai Energy Efficiency Center
11:00 Bus transportation
12:00 Lunch
13:00 Visit to company recommended by Shanghai Energy Efficiency Center
15:30 Jin Shan Waste Power Plant in Jin Shan County
17:00 Bus transportation
18:30 Arrival at hotel

Friday January 30st 2015

08:30 Leave hotel/ Bus transportation
10:00 Kone
11:30 Working Lunch at Kone
12:30 Bus transportation
14:30 Shanghai New Energy Center for Technology Transfer and Industry Promotion, contact person: Ms. Zhang Bei
16:00 Bus Transportation
16:30 Arrival at Hotel
17:30 Bus transportation
18:00-20:00 Closing dinner Utsuwa Restaurant

Saturday Jan 31 2015

06:45 Leave hotel/Bus transportation
08:00 Arrival at Pu Dong airport

5 *Shanghai Study Tour Reports*

Sunday January 25th–30th, 2015

Team Finland introduction in Shanghai

Mr. Ding Ma from Consulate General of Finland in Shanghai gave us a nice overview on the Finnish activities in Shanghai. FinChi platform has been created for Finnish SMEs to help to come to China, to speed up the internationalization of Finnish businesses as well as to guarantee that Finnish companies, especially small and medium size companies, have access to high quality, comprehensive internationalization services. Finchi provides for Finnish companies relocations services and an office hotel services, so that the companies do not need to tackle the Chinese bureaucracy at the early stage. Whereas, for the Chinese collaborators the FinChi platform offers a single contact point for various Finnish government organisations such as Finpro, Tekes, Sitra and Team Finland.

Mr. Ding Ma works mostly within field of communications and cultural affairs, and described how cultural exchange takes place between Finland and China. For instance, the Mayor of Shanghai is visiting the city of Espoo and Lahti Symphony Orchestra is visiting Shanghai in the spring of 2015 to play Sibelius in the framework of the composer's 150 anniversary. In the context of technological co-operation Finpro has been involved in Tekes's Beautiful Beijing project. The project aims to improve Beijing's air quality by Finnish cleantech, a great example of which are for instance Oilons gas burners about which we heard more on the visit to their premises.

Aalto-Tongji Design Factory

Aalto-Tongji Design Factory (ATDF) is an academic partnership between Aalto University in Helsinki and Tongji University in Shanghai. In 2010, ATDF was found and established to Tongji University campus in Zhangwu Road, Shanghai, under Sino-Finnish Centre (SFC). The collaborated platform provides pedagogical cooperation programmes including its first Double Degree Master's Programme – the International Design Business Management (IDBM) - and other student exchange programmes between the two universities. The programmes enable and inspire interdisciplinary co-creation, interaction and learning between students, teachers, researchers. Furthermore it contributes to the practical contexts of the industrial sector of the two cities. In short, ATDF forms a knowledge platform to share design philosophy and experiences between Helsinki and Shanghai.

It was the first day we arrived in Shanghai after a ten-and-a-half-hour flight from Helsinki. However, the presentation and talk by Jami Sarnikorpi of ATDF was indeed enjoyable and the jet-lagged symptoms we had seemed to fade away. Jami has been the Project Manager of ATDF since August 2013 and is in charge of the programme development in ATDF. He is a young energetic man who has previously graduated from the School of Engineering in Aalto University. Now he is living and working in a different city that infuses him with a spirit of adventure in anticipation of a new education system in China.

Jami gave us an impressive speech. "*Innovation is everyone's motto, but are they really doing it?*" he queried. He continued to explain to us that the deeply rooted Chinese education culture is indeed a challenge to the open-minded pedagogic principles of Design Factory. To be flexible and innovative is important in the constantly changing world. This is true especially for China which is at developing rapidly. At this take-off period, the open learning platform of ATDF provides a new experience to the local students by widening their vision to the international scene. Jami told us that the students are becoming more active and liberal after participating in the programmes. Despite the many questions and uncertainties raised in that afternoon discussion, Jami has a vision that ATDF could mark a long-term influence on the Chinese education system. Finally, the talk gave us a better understanding of the collaborated programmes in Shanghai and more importantly, the enthusiasm of ATDF for the design education in China.

Monday January 26th 2015

Tekes & Finnode

Innovation consul Sari Arho Havrén from Tekes Shanghai gave us a broad overview on the specialities of conducting business in China. First we discussed why to come to China in the first place; the reason is that for a business to be global it has to be in China due to the sheer market size. Also, majority of the competition can be found in China. Often, the product needs to be customized to the Chinese market, the high-end products need to be modified into low- to mid-range products in order to be able to sell them in China.

A special feature of the Chinese markets are that more or less everything is being managed from Beijing, which makes it a must to have some kind of connections there. Also, it means that political decisions may alter the business environment in a fast and unpredictable way. A good example of which is the recent introduction anti-corruption act, which has practically removed bribery. However, these kind of act might also be used to protected Chinese markets from larger foreign players.

Chinese companies are becoming, if not have become already, very difficult competitors for many markets. They are strong in applied innovation i.e. bringing value to the market, which often manifests itself as low- to mid range versions of products that are common in the western markets. For instance, Xiaomi is bringing iPhone like products aimed at Indian and Chinese customers. Another good example is PYD, which is the largest supplier of rechargeable batteries in the globe. Their innovation was to develop a lower cost fabrication environment for batteries than their competitors were using. A distinctive feature with the Chinese companies are that they listen to their customer and implement the changes in a fast pace which can be as fast as in weeks. A possible cycle is that once a week companies ask for improvements and they might also apply them in a week.

Chinese market also provide possibilities for Finnish companies for instance in cleantech due to the vast environmental problems in China. This was a topic we heard a lot more when visiting Oilon later the week. Nevertheless, China has also began to move the polluting factories to different regions.

Finpro Shanghai & Finchi

After the inspiring presentation by Ms. Sari Aho Havren form Tekes & Finnode we continued with Ms. Xia Li form Finpro Shanghai. She gave insights how Finland should be standing out in order to be one of the tops Chinese traveling attractions. Finally, Ms. Joan Zhang completed the purpose of Finchi Innovation centre. The centre is bringing companies to the same premises with the government organizations which has been fruitful for the exchange of information. Also, it was pointed out to us that the government organizations have better access to Chinese local officials that if the companies were to contact them directly. For intense, in a case if a Chinese company does not deliver or make a payment, they might be able get help from the Chinese officials.

Prof. Long WeiDing

Prof. Weiding gave to us a very detailed presentation on the status of China's energy system. We learned that China, with its 1.247 billion kW installed capacity of power generation, exceeds the U.S. and is the top country in the world (1.8 times the capacity of the EU). The main reason of China's environmental challenges is in its 66% of energy production coming from coal, while at the moment still less than 10% comes from renewable sources. However China has the largest offshore wind farm and their plan is to increase much more on the wind power compared to solar.

The share of energy consumption in different sectors is different in China compared to the western developed countries: building sector (commercial and residential) accounts for less than 20%, while in Germany it is 47%. Interestingly, the per Capita energy consumption is 2.1 toe and has exceeded the world average; however still being only 1/3 of the US per capita consumption.

We also heard about the recent China-US agreement, where the Chinese government promised reduction of emissions after 2030. We learned that they will try internally to achieve that goal already by 2025 (so that the energy peak will be achieved at 5Gtce).

In China, the electricity, oil and natural gas, the grid, too, are state owned. They have now started the change to open the market for renewable energy entrants. Professor stated that the chances are now high for private, even foreign companies, in the renewable and distributed energy sector.

IBM GCG University Partnership Operations

IBM (International Business machine) established in 1911 is an American multinational company working in the field of computer hardware and IT consulting. Traditionally, the company was known for its excellence in computer hardware. However, from 90's it has seen a series of transformation to become an IT service company. IBM research established in 1945 has established legacy of world class research. The research portfolio constitutes 12 research labs around the globe that employs over 3000 researchers. Each of these research labs have their own area of focus. For example, research lab in Dublin has speciality in smart city, Australian and Brazilian lab on natural resources. The researches in IBM lab are software and service oriented researches for business purposes. These researches thrives on data pillar; data driven insights and value, cognitive reasoning, data mining and natural language processing with focuses on cloud, mobile, social network and security based research and services. IBM ranks as the global leader as patent generator and also boasts Nobel laureates and a Millennium Technology Prize winner.

IBM research in China has also been involved in energy and environment related projects as China faces huge challenges in those fronts. China has set long term goals of reducing air pollution, increasing share of renewable energy and reducing energy consumption through efficiency. This opens up lucrative market opportunities for business. For example Beijing plans to invest 120 billion dollars in clear air projects. IBM research lab is involved in the project Green Horizon that aims for green and harmonious society in China. The Green horizon project focuses in the air of air quality management with the use of IBM modeled technologies like cognitive modelling and data assimilation. IBM is also leveraging its knowledge and expertise in smart grid transformation, area where it has been a leader for almost a decade; for smarter energy management in generation; forecasting for wind, solar and hydro power generation; outage planning, fault detection and grid assessment, and consumptions; power saving analysis.

The presentations from Harriet Cao, Jean Li, and Stephen Chu were insightful and interesting. It provided good round up summary of IBM, IBM research lab and IBM China's business. Even though the range of topics discussed was wide, the presentations were quite connected to the theme for the course. Participants demonstrated curiosity in

Watson analytics and artificial intelligence which was the highlight of the presentations. Watson, a product of IBM software division, is an artificial intelligent based computer system that is capable of answering questions posed in natural. The ability of Watson to use complex reasoning, analysis and judgement makes it a fantastic platform. It came to limelight after its battling performance with human in jeopardy game. Watson has been in commercial use from 2011, mostly in English. New application areas of Watson are health care; diagnosis, treatment assistance and notably in oncology, financial services; wealth management, government services and contact centers. Participants were curious about the reliability of system, data security and intelligent machine taking over human. The discussion concluded with the notion that artificial intelligence will just eliminate more routine and boring tasks rather than replacing humans. The fact that speech recognition and machine translation are so difficult already give a glimpse that machine overtaking human is quite a distant fact.

Sino-Finnish Centre, Tongji University: a creative meeting point of education and innovation

Tongji University was founded by a German physicians in 1907. Established as a medical school, today Tongji university is highly valued as among the group of leading engineering schools in China. However, It was not until 1927, Tongji University moved to engineering. In 1978, Tongji became among the group of Chinese university to collaborate with the foreign University. The University has 4,000 graduate students, 10,000 master's students and 26,000 bachelor's student. Major disciplines in Tongji are urban construction and disaster prevention, modern manufacturing, biomedicine, and design and innovation.

The Tongji University has international collaboration with universities in Germany, France, Italy, Spain and Finland. The partnership between Aalto University and Tongji began from 2010 when Aalto participated in the Shanghai Expo. The partnership gained physical shape in the form of a Sino-Finnish center. The main focus of the center is to provide an interdisciplinary academic track as well as good collaboration connections with the Finnish industry. Tongji Design Factory was established with the purpose of introducing a student oriented learning approach. The teaching was based on experience and passion based learning. The factory was designed around Stanford partnership model that emphasizes on entrepreneurship.

Even though Tongji design factory visit was at the end of a long day schedule, the creativity embedded in the atmosphere gave interesting and refreshing impression. Starting from innovative design of the elevator, to factory layout and comfortable looking presentation hall, it had design thinking written all over it. The presentation provided insightful information about Tongji and especially, Chinese way of teaching. The idea of changing the way of teaching and learning with high student involvement, design thinking and cross-cultural learning was interesting. The participants were curious about the differences Chinese and European in teaching approaches, cross-cultural environment, entrepreneurial outcomes. Some participants also expressed their desire to join Tongji as postdoctoral researchers and research exchange.

Tuesday January 27th 2015

Shanghai Research Centre for Wireless Communications

Shanghai Research Centre for Wireless Communications (WiCO) is a non-profit organization co-founded by Chinese Academy of Sciences (CAS), Shanghai Institute of Microsystem and Information Technology (SIMIT), Science and Technology Commission of Shanghai Municipality (STCSM), Southeast University (SEU) and Changing District Government in November 2003. WiCO consists of active researchers and experts and is focused on the R&D of the key technologies for future broadband wireless mobile communications. WiCO has successfully undertaken many key research projects from the Ministry of Science and Technology of China (MOST), the National High Technology Research and Development Program of China (863 Program), the European Union Framework Program, CAS, STCSM and telecom industry, covering new air-interface and wireless networking technologies, system integration and performance evaluation, field trials and demonstrations of integrated broadband wireless services, as well as standardization activities at 3GPP and ITU. Through these projects, WiCO has established broad R&D collaborations with many national and international academic and industrial partners in the areas of wireless mobile communications. On the day of our visit, the Bit Bang delegation was received by Haifeng Wang, an alumni of Tampere University of Technology. Hai Feng led the introduction and presented the background activities of WiCo, their roles and research focus areas. Wico's activities are to help the government to select new research areas. It also aims to be the business link to local and international industries for academia. Wico is involved in generating research ideas (5 years), creating solutions (2-5 years) and package the solution to be deployed in industry (less than 2 years). WiCo is thus focussed on shorter term applied research, rather than long-term, "magic carpet" research.

During Hai Feng's presentation, questions were posed about the process of standardization and IPRs (intellectual property rights). The standardization body is formed under the international communication organisation, which is one of United Nation's (UN) sub-agencies. The consensus on global standard is reached through the conferences in UN. It forms the essential patent with the agreement among all member states. This official body usually plans 10 years in advance and the information is open to all field players. WiCo, as well as other wireless R&D organisations, builds on the body with specific functions and scenarios. Moreover, the process is interruptive and interactive between the official body and the regional organisations.

5G technology was mentioned and related product is being tested on a small scale, for instance, a campus-based scale. This is done through bilateral monitoring and modification, which means that the concerned software is installed on students' or users' cell phones. The feedback can be returned to centrally controlled computing system to calculate and test the new technology.

Another noteworthy application of wireless technology discussed is in the multi-decade infrastructure mega project called the South-North Water Diversion Project, which aims to channel large amounts of fresh water from the Yangtze River in southern China to the more arid and industrialized north through other canal systems. The wireless technology application constitutes the installation of wifi sensors along the Yangtze River, thus allowing the capture and integration of relevant infrastructure asset management data.

After the presentation and discussions, the Bit Bang delegation was taken on a tour through the facility, where some of the current research projects were shown.

Valmet (China) Co., Ltd

The Valmet Corporation is a Finnish company, a leading global developer and supplier of services and technologies for the pulp, paper and energy industries. It was founded in 1951, with roots back to 1700's. It was reborn through the demerger of the pulp, paper and power businesses from Metso Group in December 2013. Valmet is organized around three business lines which are Services, Pulp and Energy, and Paper. The company has operations in around 30 countries and employs 11,000 people with annual revenue approximately 3 billion €. In China Valmet's got approximately 2000 employees in production, sales and service units. The sales in China in 2013 were 389 million €, which makes China Valmet's largest single country in terms of net sales. In pulp and paper Valmet is the leader in China with market share of 30-40%.

The Bit Bang visit started with a tour of the factory and production facilities, led by several Valmet personnel, who helped answer many questions during the tour. The tour was followed by the presentation by Aki Niemi, where an overview was given about Valmet's history. He also explained the reasons for locating their factory to China, of which the motivations were mainly the accessibility to resources and the potential markets. Valmet's competitive advantage is highly attributed to their packaged solutions in process automation. Their lifecycle service of plant and equipment (including operation and maintenance) is highly regarded. However, in China, most of the customers are in pulp and paper segments.

By the end of the presentation, Mr. Aki Niemi said, "standard is one thing, yet quality requires much more efforts than that. We cannot be too proud but humble."

ERA Acrobat show

Our day ended with the attendance of an acrobatic performance at the Shanghai Circus World theatre. Era was performed by many types of acrobats with the integration of theatrical elements of live music, multimedia, costumes, drama and special effects. It was a profound and astonishing performance capturing deep tenderness through the expression of human form with the most impressive precision and control. The story line constantly warped between the past and future and created remarkable contrasts between different interpretations of the acts. Motives in traditional Chinese folklore fused gracefully with the parody of modern pop culture to achieve the story.

The show was driven by powerful mood transitions, brought about by the surprisingly well-crafted scene metamorphoses that seemed to trick the mind of the audience into believing in its effortlessness. A great part of the magic of the performance was the seemingly subconscious stage set changes from one state to another, devoid of awkward props or stiff variations. Even the music was seamlessly blended with the performers and multimedia projections.

Needless to say, Era exceeded most of our expectations evoked emotions through their beautiful performance - every now and again lifting the audience off their seats in anticipation and suspense. Even the most technical of doctoral research seemed to have found some trace of artistic inspiration from the experience.

Wednesday January 28th 2015

Oilon Ltd

Oilon is a family owned Finnish company, headquartered in Kokkola, active in the area of heating industry (gas combustors) and ground heating (heat pumps). During our visit to the company's facilities in shanghai, we were briefed by its general manager of China operations Mr. Sami Pekkola. In addition to updating us about the current status of this industry in china and the future threats and opportunities he also took us on a assembly line visit were the Oilon makes and tests its gas combustors and heat pumps. He explained the compressors as a type of fire gun that produces high quality flame without producing much exhaust pollution. Also he talked about the heat pump as a method of utilizing the geothermal energy to produce heating and cooling through the use of boreholes as required.

Oilon products range from smaller household solutions to industrial items. Oilon has operations in five continents moreover it holds the highest market share in Finland while the competition from big names such as Johnson Control and Bosch exists in the global markets like China. Mr. Sami Pekkola admits that German competitors are well known for their excellent quality products however Oilon has the upper hand when it comes to services and flexibility towards customers' needs, therefore they are able to favorably position themselves in the Chinese market.

We were told about the opportunities which were raised from the governmental emission policies and how Oilon was able to utilize its know how developed in Finland for clean combustors technology to establish its position in China market. The future targets by the Chinese government as they become stricter seems to be even more promising to improve the Oilon's market position.

During our line visit we understood that Oilon is mainly working with boiler manufacturers and they are not directly involved with the customers till there is a need for after-sales services. This enables Oilon to standardize their products according to different categories of boilers and streamline their operations. We also were told about the two incident that Oilon's IPR were infringed By Chinese manufacturers and how the company confronted those with legal actions. But overall they don't see any big threat from the independent copiers than they see from their boiler manufacturer partners therefore they still continue to patent their innovations to protect them.

One of the interesting pieces of information that we understood was the trend towards the utilization of additive manufacturing to make the combustor's covers. The experimentation now is ongoing in the company's Finnish production unit.

Wuxi New District: Internet of Things

Wuxi Sensing Net Industrialization Research Institute was founded in November, 2009. To meet the needs of national strategy and major scientific plans, the Institute emphasizes the activities on designing and improving the value chain of IoT (Internet of Things) industry. Playing a leading role in the 3rd revolution in information industry, the institute has laid a technical foundation for the establishment of "Sensing China Center" in Wuxi, thus making an outstanding contribution to the national technology innovation and economic restructuring. The ambitious project involves several research institutes, including Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences (CAS), Nanjing University of Aeronautics and Astronautics, Northwestern Polytechnical University of China, with strong support from Chinese government. Researchers disclose that they have made certain achievements in the research.

China is speeding up on development of "Internet of Things", making it a new engine for economic growth and an opportunity to catch up with the developed countries. "Internet of Things" is a number of technologies and research disciplines that enable the Internet to reach out into the real world of physical objects. Technologies like RFID (Radio Frequency Identification Device), short-range wireless communications, real-time localization and sensor networks are now becoming increasingly common, bringing the Internet of Things into commercial use. They foreshadow an exciting future that closely interlinks the physical world and cyberspace - a development that is not only relevant to researchers, but to corporations and individuals alike.

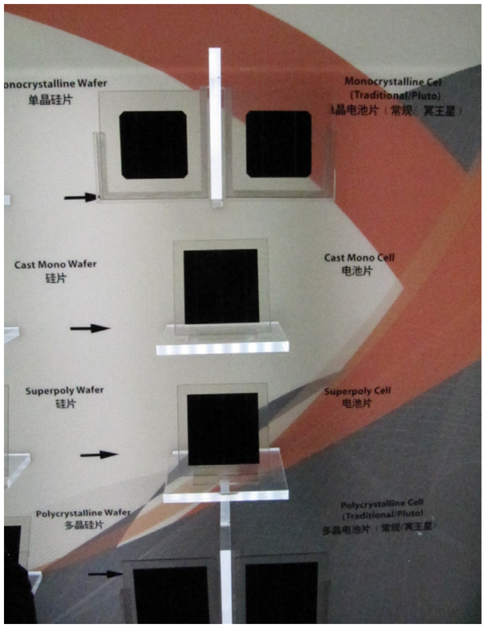
During out visit, IOT applications such as traffic flow and surveillance, early-warning of traffic accident, Parking guide &management, Driving security, Guard against theft and alarm system , alarm system for natural gas leaks, Remote surveillance of house have been demonstrated to us.

SunTec Wuxi

On Wednesday afternoon we visited Suntech Wuxi, a solar energy company, founded in 2001. Suntech's got the head quarter in Wuxi, China, and regional branches in London, Tokyo, Johannesburg and Sydney. In April 2014 Suntech officially became part of the Shungfen Group.

Suntech develops, manufactures and delivers reliable and cost-effective solar energy solutions. The capacity of the first production reached 10MW in 2002. By February 2014 Suntech had passed 25 million units of solar modules, with total capacity of 8 GW.

Suntech produces monocrystalline and multichrystalline solar panels. One of the products in the 'Light Thru' solar module, which is at the same time both power generator and aesthetic sunshade. Customized panels with desired size and light levels passing through the glass can be used in versatile building projects.



Solar Industry representative panel discussion

In the beginning of the meeting we were told about the history of the Wuxi new district and how it was established in 1992 as an industrial zone. Currently Wuxi is home to many companies in various industries such as equipment, renewable energies, biotechnology and software among others. One of the significant facts about this district is its considerable annual photovoltaic (PV) production capacity (two GW) which corresponds to twelve percent of world production capacity.

In China the government incentives are the main reason for the expansion of PV application in a distributed setting. These incentives are given as payments per kilowatts of renewable energy produced directly to the producers. As the speakers confirmed, the solar energy at the current rates are not competitive with other types of energy production in terms of cost, therefore the role of government is crucial at this time.

Speakers talked about the potentials of a distributed renewable power generation enabled by solar cells for homes and how that might reduce the dependence of China on coal and pave their road to a greener economy. However, as the household consumption is minor when it is compared to the industrial use, this solution needs to be seen in action before we can confirm its impact level. Currently the power storage in the distributed setting is the most challenging aspect as the existing technologies are cost intensive. Moreover, the distributed PV energy generation is also problematic from the production and demand perspective as the amount of production exceeds the demand in summers while it's not enough in winters.

The distributed production is based on principles of economic feasibility including where to receive the highest subsidies and the existence of consumption locations which might translate to the people's density per square meter of accommodation.

Another point that were discussed was the potential for a significant PV implementation in western China, however since the main energy consumption centers are located on the east coast, it will require efficient transmission methods which are lacking at this time.

Thursday January 29th 2015

Shanghai Energy Efficiency Center

As a working unit under the Shanghai Municipal Commission of Economy and Information, Shanghai Energy Efficiency Center (SEEC) carries out energy efficiency policies, energy efficiency evaluation, information distribution and other aspects of energy efficiency promotion like social activities and technology transfer. The Bit Bang 7 delegation was first presented with an overview of the operation of the center, including a summary of the incentives that Shanghai has to offer for industries. Shanghai municipality is dedicated to promote energy efficiency, and they have a surprisingly advanced system in terms of practical support: 300 REM is provided to companies per each saving unit which is defined as 500 coal equivalents (coe, where one coe equals to 0.7 oe). For getting the support, SEEC requires a good measurement system: many of the center's activities are aimed to evaluate the energy efficiency and emissions of technologies. Near Shanghai, around 400 companies are currently registered to match the requirements for the support, and also foreign companies are encouraged to join. According to the five year plan of 2011, these incentives are extended all the way to individual consumers, who can receive revenues when buying the environment friendly option of suppliencies like energy efficient computers or electric cars. In addition the energy saving incentives, commitment to energy efficiency is also encouraged with reduced taxation, which include 10% less payment for income tax and refunds from VAT. One the other hand, benefits are accompanied with penalties, which are collected if energy use is more than predicted.

Upon arrival, we were pleased to hear that SEEC had already made some connection to Finland: in 2013 they organized Green Designing Seminar together with the Finnish Embassy. Also Joensuu bioindustrial park was mentioned as a reference to provide information of the concept of green industrial parks. In 2014, five green industry parks passed the assessment of SEEC, and the aim is to have more established in 2015. SEEC has defined 22 criteria and standards, including measurements for water use, volatile organic compound emissions, energy efficiency for building and transportation, which the industry park has to pass to become labeled ”green”.

As SEEC is mainly working on municipal level, the discussion turned also to the management of the city and grid use issues. The huge size of Shanghai raises the question if it is already unsustainable in terms of energy. This is taken into account at the moment by controlling expansion and transforming industries, mainly moving some industries out of the city with the workers. For optimizing the grid use, Shanghai already has a system of differential electricity pricing. For residents, peak hour is double the price and for industry there are three levels of pricing from low hour to peak hour. Maybe this is one of the reasons why peak electricity use in Shanghai is not at a big level compared to the amount of people. The buildings of the city are also an issue since they consume 20% of the total energy. The fast growth also provides an opportunity to apply new standards for new, more energy efficient buildings, which appear to the Shanghai skyline weekly.

Although promoting, evaluating and implementing energy conservation strategies are a central aim of SEEC, the center also works in raising public awareness in energy efficiency issues. SEEC works together with organizations to have happenings at community level, like the energy saving week in June. They also work with schools to educate youngsters about energy efficiency. Also companies registered to receive the energy saving support are required to realize social and environmental benefits in addition to energy savings. Social benefits in this context also include the option for public surveillance: people can make a complaint if some company is not following their commitment to energy efficiency. As the main municipal agency of energy conservation, SEEC is constantly seeking new ways to save energy by promoting existing solution and looking for new important innovations.

Solar Power Company

Shanghai Solar energy research center 's main research fields are development of technology and equipment of PV materials , PV cells and PV testing, design and integration of BIPV systems, and consulting services and industrialization matching of PV. The center's task is also to promote the development and utilization of solar energy technology and act as a research platform between industry and academia. To train professional and technical personnel, they do cooperation with e.g. the

Shanghai Institute of Space Power Center, Shanghai Jiaotong University and Institute of Aerospace air power technology.

We started our tour with a miniature of different buildings that deploy solar energy. The miniature included e.g. China pavilion in Shanghai world expo, and we were told that its shape was inspired by design of traditional hats used by Chinese officials.

Next we went to an exhibition room where several examples of materials and latest innovations developed by the center were shown to us. Those included e.g. chips that used for satellites, soft solar panels for military use, and an energy-efficient optical fiber lamp. We also saw raw silicon which was in poly-crystalized form.

Then, the final culmination of our visit was pilot production line. Pilot production line is used for the experiments and the actual production takes place at mass production line, which is in another location. We were told that they produce panels both for industrial and household use. In China, also the household-level use is encouraged, as families that are connected to national grid can supply their micro-produced energy back to the grid, and get 14 cents from the government for each unit produced.

We got a very hands-on and in-depth introduction to the structure of solar panels. They consist of different layers. First layer is glass, the second layer is EVA, then battery, and, finally, another layer of EVA. EVA is sheeting material that protects the panels, as solar cells are very sensitive to moisture, oxygen and weather. The layers are assembled together with a specific machine, and also EVA layer is melted in that process, during which it turns transparent. Finally, the panels are laminated. We also saw the laminator machine. We also saw something "fresh from the oven", a solar panel that was produced earlier that day. Our guide Helen called the final product as a "5-layer sandwich".

The visit was very interesting and a lot of questions were asked. Some of us got really excited about the possibility to see the complete process of producing solar panels in an assembly line.

Jin Shan Waste Power Plant

The Jin Shan Waste Power Plant was opened in December 2012. The power plant has two waste management lines, each capable of handling 400 tons of waste per day. The plant is planned to treat 266,400 tonnes of municipal waste annually. Collected waste is incinerated and the heat generated during incineration will be recovered to produce electricity by utilization of a steam turbine generator with the capacity of 15 MW. The average electricity generated annually will be 94,246MWh and 78% of the total output, which amounts to 73,512MWh, will be exported to the East China Power Grid. Currently, the heat generated during the electricity production is not utilized. Thus, the energy conversion efficiency of the incineration process is only about 30 %. If the heat could also be utilized, this would rise to around 80 %. Utilizing the heat is currently at a planning stage. It is estimated, that over a 10 year period, the power plant would save roughly 1 million tons of CO2 emissions, by avoiding methane emissions in waste landfills and by replacing coal generated electricity in the state grid.

During our visit, we got a first-hand look at the operation of the facilities when the factory manager took us for a tour around the power plant. We saw the waste storage room, where the waste is brought by waste trucks. The room typically stores around 10 000 tonnes of waste. The waste remains there for roughly 7-8 days, where it combusts and dries. The waste water is collected and properly sorted, and the generated methane is burned in the waste incineration process. After the waste is properly dry, it is taken into the incinerator. The incinerator burns the waste at around 900 C, heating up air which is driven through the turbine to generate electricity. After incineration, the remaining dust and other waste is collected and stored.

Friday January 30st 2015

Kone

On Friday morning our bus headed to Kunshan, where KONE had opened a new KONE Park manufacturing site, engineering facility and research and development center in 2014. R&D Manager Tommi Niinivaara introduced us to KONE's business in China, a well-developed business, which started already 30 years back in 1985.

The first elevator factory was opened in Kunshan in 1998. The new KONE Park with appr. 40.000 m2 of production area and with a plan to build 10.000 m2 more has more than doubled the production capacity. The plant produces commercials escalators and ramps, heavy duty escalators, auto-walks and elevator components: cars, machinery and electrification solutions. Today, KONE is the #1 in elevator sales in China and the sales in China comprise 30% of KONE's sales worldwide. 67% of the new elevators produced by KONE are installed in China. KONE's got approximately 10 000 employees in China.

The megatrends driving KONE's growth are: urbanization, safety, changing demographics and environment. The fast urbanization in China, aging population and higher standard of living in the future set demands for high buildings, shopping centers, metro lines and megacities.

KONE has practiced in China a dual brand strategy, which has been very successful. In 2005 KONE formed a joint venture, GiantKONE Elevator Company Ltd, and in 2011 KONE became the majority stakeholder of the company. KONE takes care of the high end market, e.g. 5* hotels, malls and metro lines. GiantKONE takes care of the low end market, e.g. residential houses.

Buildings account for 40% of the world's energy consumption and elevators account for 2-20% of a building's energy consumption. KONE's elevators have got an energy label and KONE was one of the first companies to get an 'A class' certification for it's elevators. Energy issues are important also in China and Green construction market size has grown for 300-400 % since 2010. This brings a huge market potential to KONE. With innovations and improvements KONE has been able to lower the elevator energy consumption by 70%.

After the presentation we had a tour around the manufacturing site visiting the elevator and escalator production. KONE also offered us a nice lunch.

Shanghai New Energy Center for Technology Transfer and Industry Promotion

Our last stop was at the Shanghai New Energy Center (SNEC), which works closely with research organizations and the industry to ensure easy tech transfer between the two. We met Dr. Yonghao Luo there, who is the Chief Engineer of the center. He gave a presentation about the center and the energy situation of Shanghai. After the presentation, we had a question answering session for around 30 minutes.

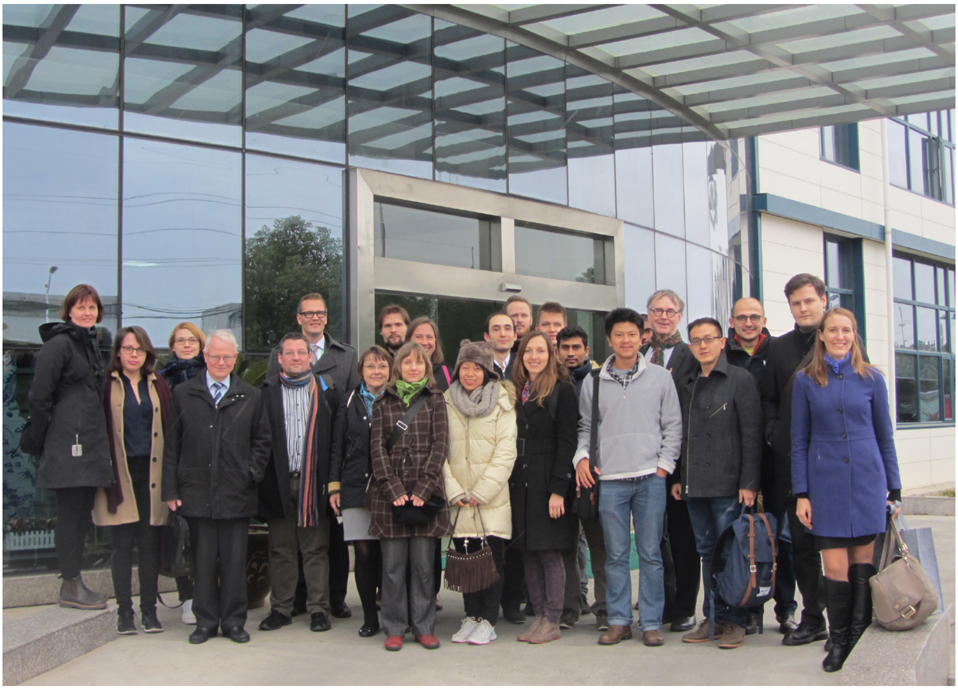
In China, the government manages all forms of energy, including all efforts for new energy technologies. SNEC thus acts a bridge between various research organizations and the government. It mainly focuses on two aspects: (i) Perform research in the development of new energy technologies and energy saving, and (ii) Work closely with research teams and transfer the research into industry, which includes doing feasibility tests for new research prototypes. Dr. Luo explained about how Shanghai is hitting the limit in terms of energy needs and how the Shanghai government wants to prepare itself for the challenges ahead.

In his presentation, Dr Luo explained firstly explained how Shanghai is currently the main sources of energy for Shanghai are from outside of Shanghai, which is mainly dominated by coal (46%), gas (9%), and crude oil (33%). There are 3000 coal industrial boilers which will be closed by 2017 and replace by gas. A major portion of this energy is used by the industry, transportation and buildings. To counter this, new technologies are being researched in these areas. He showed us what SNEC was working on each one of these areas.

1. Energy saving in buildings: SNEC has built and tested energy saving buildings which can save upto 75% of the energy by integrating with renewable energy and recycling resources efficiently. He also pointed out that these buildings, though very useful, are not practical because of their high cost. He said that they were working on getting the costs down.
2. Energy saving in transportation: SNEC is working on lowering emissions from large scale transportation systems, like buses and taxis by enforcing conversion to gas. This ensures not only energy saving, but also lesser pollution. He also showed examples of prototypes they built of an ultra capacitor bus (which is already commercial) and a fuel cell taxi.
3. Energy saving in industry: Dr. Luo explained that currently, 80% of the electricity for industry is from coal. He explained that the government has set a deadline for the companies and by 2017, 3000 companies based on coal will be closed down. He said that they were trying to move from small coal fired plants to large super-critical power plants, which are 20% more efficient. They were also working with the government to set up waste gas emission standards, which reduce the emissions from the industries drastically.

Closing dinner

We had the closing dinner at a Japanese Fusion restaurant. We had a short discussion about the experiences we had during the trip, where most of the students expressed very positive experiences about the trip. After the discussion, we had some awesome Japanese food, with wine and beer. This was followed by group presentations, where each of the 4 groups was supposed to present something creative and interesting about their experiences during the trip. The first group presented a quiz containing fun facts about each of the students. The second group had play showing how the earth was being polluted and affected by various actors like industry, people, etc. The third group made a satirical video showing how Hitler was angry about the progress China has made in renewable resources. The fourth group tried to emulate the ERA Acrobat show, which we have been to during that week. After that, there was the award ceremony awarding the team with the best performance and also one who asked the most questions.



This book is the 7th in the Bit Bang series of books produced as multidisciplinary teamwork exercises by doctoral students participating in the course **Bit Bang 7: Future of Energy** at Aalto University during the academic year 2014–2015. The course aims at fostering teamwork and multidisciplinary collaboration, as well as providing participants with a global, future-centric perspective on the energy sector.

The growing global demand for energy and diminishing natural resources are driving the development of eco-efficient energy sources, new ways of doing business, and designing our living environment. Bit Bang 7 addresses the topic of energy sources and technologies from the perspective of their economic, environmental and social sustainability. The course elaborates on the interconnectedness of these phenomena, and links them to possible future scenarios, global megatrends and ethical considerations. Will we see disruptive changes in our energy future? Can we impact consumption patterns, ways of doing business, and our way of life? Are we creating a sustainable future for the generations to come?

Working in teams, the students set out to answer questions related to the changing energy sector and to brainstorm radical scenarios of what the future could hold. This joint publication contains articles produced as teamwork assignments for the course, in which the students were encouraged to take novel and radical views on the future of energy.

The Bit Bang series of courses is supported by the Multidisciplinary Institute of Digitalisation and Energy (MIDE). Previous Bit Bang publications are available from *http:/mide.aalto.fi.*

ISBN 978-952-60-1097-7 (printed), ISBN 978-952-60-1098-4 (pdf)

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